Evaluation of software tools in performing advanced evacuation analyses for passenger ships

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Abstract

As safety regulations for passenger ship design continue to advance, so does the need for evacuation analysis tools to simulate the evacuation process. Currently the IMO requires an evacuation analysis for all new passenger ships in one of two ways: a simplified analysis or an advanced analysis. The simplified analysis takes a macroscopic view of the problem, treating the evacuees as particles in a fluid, flowing to their muster stations through corridors and doors as if they were pipes and valves. On the other hand, the advanced analysis takes a more microscopic approach, treating each evacuee as an individual with their own behaviour and decision making. However, as crowd simulation on passenger ships is a relatively young field of study, there is no clear consensus on the best way to perform this advanced analysis and therefore the guidelines are left more open ended. Consequently, there are several software suites that perform the analysis in different ways.

This study aims to evaluate and better understand two different software packages, Evi and Pathfinder, which are capable of performing an advanced evacuation analysis. To do this, the same evacuation scenario on the same Main Vertical Zone (MVZ) of a RoPax ferry was simulated on both software in order to see how the differences in approaching the modelling affected both the numerical results and the user experience, including the time taken to build and run the analysis. These results were further compared with those obtained from a simplified analysis.

Despite differences in how the reaction times were distributed, the total completion times measured were very similar, falling within the acceptance criteria set for this study. However, the user experience is where the largest differences between the two software became apparent. While Pathfinder had a more feature-rich toolset to build the geometry, the fact that Evi is purpose built to perform evacuation analyses of passenger ships is apparent in its preset IMO cases and batch running capabilities, providing a clear time advantage in performing the task.

Keywords Passenger ships, Evacuation analysis, Crowd simulation, Simulation software

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Tiivistelmä
Laivasuunnittelun turvallisuusmääräysten kehittyessä, myös evakuointianalyysityökalujen tarve matkustaja-alusten evakuointiprosessin simulointiin kasvaa. Tällä hetkellä IMO säännöksissä vaaditaan kaikkien uusien matkustaja-alusten evakuointianalyysi tehtävän joko yksinkertaistetulla tai edistyneellä analyysillä. Yksinkertaistetussa analyysissä otetaan makroskooppinen näkymä ongelmasta käsittelemällä evakuoitavia kuin ne olisivat partikkeleita nesteessä, virraten kokoontumisasemaansa käytävien ja ovien kautta, ikään kuin nämä olisivat putkia ja venttiilejä. Edistynyt analyysi taas noudattaa mikroskooppista lähestymistapaa. Tarkastelussa kukin evakuoitava henkilö on yksilö, jolla on oma käyttäytymisensä ja päätöksentekonsa. Koska matkustaja-aluksien väkijoukkojen simulointi on suhteellisen nuori tutkimusala, ei ole selvää yksimielisyyttä parhaasta edistyneen analyysin tekotavasta tai yksityiskohtaisista ohjeista. Näin ollen on olemassa useita ohjelmistopaketteja, jotka suorittavat analyysin eri tavoin.
Tämän tutkimuksen tarkoituksena oli arvioida ja paremmin ymmärtää kahta erilaista ohjelmistoa, Evi ja Pathfinder, jotka molemmat pystyvät suorittamaan edistyneitä evakuointianalyysejä. Yhden RoPax-lautan saman pääpalovyöhykkeen evakuointiskenaario simuloitiin molemmilla ohjelmistoilla, jotta voitiin nähdä, miten mallintamisen erot vaikuttivat sekä numeerisiin tuloksiin että käyttökokemukseen. Vertailun kohteena oli myös analyysin rakentamiseen ja suorittamiseen kulunut aika. Tuloksia verrattiin yksinkertaistetun analyysin tuloksiin.
Reaktioaikojen jakautumisen eroista huolimatta, kunkin evakuoinnin mitatut kokonaiskestoajat olivat hyvin samankaltaisia, ja ne olivat tässä tutkimuksessa asetettujen kriteereiden puitteissa. Suurin ero näiden kahden ohjelmiston välillä oli kuitenkin käyttäjäkokemuksessa. Vaikka Pathfinderilla on monipuolisempia suunnittelutyökaluja, Evi:n etuus on se, että se on selvästi rakennettu alusta alkaen laivojen evakuointianalyysiin. Tämä tulee esiin sisäänrakennetuilla IMO skenaarioissa ja eräajo-ominaisuuksissa, jotka säästävät paljon aikaa ja työtä.

Avainsanat Matkustajalaivat, Evakuointianalyysi, Väkijoukkojen simulaatio

Preface

This thesis was completed for the Nordic Master Programme in Maritime Engineering, in partnership with Deltamarin Ltd.

I would like to thank Prof. Pentti Kujala from Aalto University and Dr. Hans Liwång from KTH for their guidance and patience over the course of this project. Also, I would like to thank my advisor Markus Vauhkonen from Deltamarin Ltd, for bringing this topic to my attention, and sponsoring and supporting this endeavour. A special thanks goes to Thunderhead Engineering and Brookes Bell LLP for their support with the software.

Finally I would like to thank my friends and family for their support along this journey, especially my fiancée Kirsi, whose help was invaluable.

Thank you.

Turku, 20.04.2020

Eetu Vilen

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List of Abbreviations

CA	Cellular Automata
CAD	Computer Aided Design
CCTV	Closed-Circuit Television
EPC	The Euclidian Projection Coefficient
ERD	The Euclidian Relative Difference
FSEG	Fire Safety Engineering Group from the University of Greenwich
FSS Code	International Code for Fire Safety Systems
GA	General Arrangement
HEP	Human Error Probability
IMO	International Maritime Organisation
LSA	Life Saving Appliances
MARPOL	The International Convention for the Prevention of Pollution from Ships
MES	Mass Evacuation System
MSC	The Maritime Safety Committee
MVZ	Main Vertical Zone
RFID	Radio-frequency identification
RoPax	A vessel with large Ro-Ro decks and passenger carrying capacities
Ro-Ro	A vessel primarily used for carrying vehicle cargo intended to be rolled on and off the vessel
RSET	Required Safe Egress Time
RTD	Response Time Distribution
SC	The Secant Cosine
SFPE	Society of Fire Protection Engineers
SOLAS	The International Convention of Safety of Life at Sea
STCW	The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
TAT	Total Assembly Time

1 Introduction

For over a century there has been an international drive from the global community to improve the safety of travelling by sea. From the sinking of the RMS Titanic in 1912 leading to the creation of the first versions of SOLAS (The International Convention for Safety of Life at Sea), large-scale internationally ratified regulations on ship design are often preceded by disastrous accidents that have caused the deaths of thousands of lives. In particular, the sinking of MS Estonia (1994, 852 lives lost [1]) and MS Herald of Free Enterprise (1987, 193 lives lost [2]) led to requiring an evacuation analysis on a passenger ship design to evaluate the safety level of the ship with regards to dimensioning and layout of escape routes for its passengers [3].

Evacuation analysis is first and foremost an attempt to replicate and simulate human behaviour in emergency situations, and has been a topic of interest since the early 1950's in order to improve the fire-safety of buildings. With it, the designer is trying to simulate how a person will react and move to an emergency; how large crowds will affect movement speed; and how the layout of the space will either help or hinder the escapee from reaching their goal. This same theoretical background is used in performing evacuation analyses on passenger ships, with some adaption needed due to the uniqueness of travelling at sea.

There are several ways of performing an evacuation analysis, varying from: simple models that treat all evacuees as a single mass 'flowing' to their destination; to more complex models that simulate each individual person on the ship, their cognition level, relation to other passengers and motion within rooms. Nevertheless, due to regulations moving steadily towards requiring more and more complex simulation methods, there are several advanced software tools on the market that can accomplish this using different methods. As each software package will be based on fundamentally different approaches to evacuation analysis, it is of interest to see how these different ways of simulating the evacuation event compare to each other. Futhermore, from the perspective of the designer, the time taken to perform the evacuation analysis is an important factor to consider, as it relates directly to the cost of the project.

Therefore, this study aims to evaluate current evacuation analysis software tools. This will be done by first giving an overview on the theory behind evacuation simulation to better understand how the software is built and their underlying theory, and the different modelling methods currently in use on the market. Then, two different advanced simulation software will be compared against eachother, evaluating the numerical results of the simulation itself and the user experience of the software to better understand what effect the differences have on the end result of the analysis and on the passenger ship design process itself.

2 Literature Review

2.1 Evacuation on Passenger Ships

2.1.1 Need for Evacuation Analysis

The need for evacuation analysis stems from a desire to improve the inherent safety of a ship's design. As ship accidents are often unpredictable, it is important that procedures are in place to facilitate a rapid and safe evacuation of all passengers. One way to do this is to eliminate features in the design of the ship that cause congestion during the evacuation process; the identification of which is the primary goal of evacuation analysis. However, evacuation analysis has only recently been required by international rules and regulations and is fairly young as a field of study.

2.1.2 History of Ship Regulations

Historically, rules and regulations concerning ship design are built on the backs of major ship disasters. The first major piece of internationally ratified regulation was the International Convention for Safety of Life at Sea (SOLAS); created in 1914 as a response to the sinking of the RMS Titanic in 1912. The ocean liner was the largest commercial passenger ship of its time, which sank on its maiden voyage in the North Atlantic Ocean, killing a 1517 people out of a total of 2223 people on board [4]. One of the major issues in the disaster was that there were only 20 lifeboats onboard, and therefore SOLAS outlined the specific need for the number of lifeboats and other Life Saving Appliances (LSA) required onboard a vessel.

Since then, the International Maritime Organisation (IMO) began its work in 1959 as a branch of the UN, tasked with upkeeping and creating new maritime legislation [5], some notable conventions being:

- SOLAS 1974 (The International Convention for Safety of Life at Sea)
- MARPOL (The International Convention for the Prevention of Pollution from Ships)
- STCW (The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers)

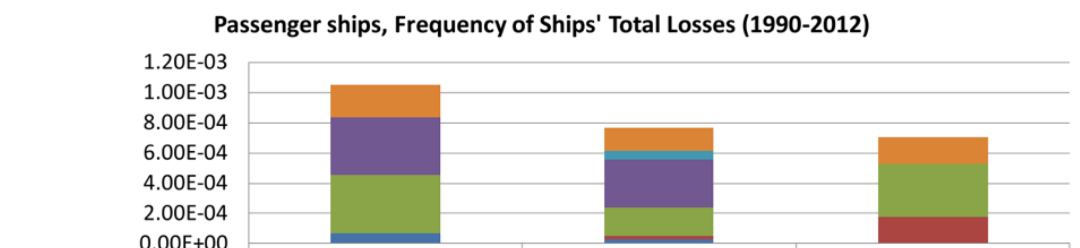
These regulations concerning ships have grown considerably in scope since they were first created, covering everything from LSA to stability requirements of the ship itself, and are constantly updated and amended to reflect advances in technology. As well as the IMO, rules tend to be set by two other bodies: The nation state under whose flag the ship will be sailing and the Classification society (often also acting on the behalf of the flag) providing official assessments of the ship.

2.1.3 Ship Accidents

As mentioned, rules and regulations concerning the operation and design of ships are primarily an attempt to minimise the occurrence and impact of ship-related accidents, which can be divided into six categories in the following forms [6]:

- **Grounding.** Contact with land.
- **Hull/Machinery Damage.** Damage to propulsion and/or other machinery required for the operation of the ship.
- **Foundering.** Taking on water and sinking due to ship instability or rough weather.
- **Fire/Explosion.** Damage to the ship due to a fire or explosion.
- **Collision.** Contact with another ship or seagoing vessel.
- **Contact.** Contact with things other than land or ships, such as marine structures.

Some modes of accidents appear more frequently on certain types of ship than others [7]. Extensive studies have been performed on accident statistics for different ship types, and according to historical data, the most frequent ship accident for Passenger, RoPax and Cruise ships is Hull/Machinery Damage as seen in Figure 1. However, when analysing results that lead to total ship losses (where there would be a higher need for evacuation), the main cause is Fire/Explosion damage, followed by Foundering and Grounding.



	Passenger Ro-Ro Cargo	Passenger	Cruise
Wrecked/Stranded	2.09E-04	1.59E-04	1.75E-04
Hull/Mchy. Damage	0.00E+00	5.30E-05	0.00E+00
Foundered	3.84E-04	3.18E-04	0.00E+00
Fire/Explosion	3.84E-04	1.85E-04	3.51E-04
Contact	0.00E+00	2.65E-05	1.75E-04
Collision	6.97E-05	2.65E-05	0.00E+00

Figure 1: Frequency of ship's total loss per ship year, Passenger ships [7]

2.1.4 Case Studies

Due to different types of accidents present in these accident scenarios, it is important to realise the different ways they will affect the evacuation procedure. Listing due to grounding or heavy weather will affect evacuating passengers differently than fire damage obstructing travel with fire and smoke.

One recent example demonstrating the difficulty of performing large-scale evacuations after grounding contact is the Costa Concordia accident in 2012, where there was a breach in the hull resulting in the grounding of the ship. By the time the evacuation order was issued, the ship was already listing up to 30 degrees; disorienting passengers trying to find their way to the assembly stations, ultimately leading to the deaths of 32 people. This was also a failure of operational procedures, as the scheduled evacuation drill was planned for the day after the accident, meaning that passengers were not aware of the procedures [8].

On the other hand, an example where mustering was ordered and was conducted successfully was during the fire of the RoPax vessel Urd in 2014 [9]. Here a fire started on the main car deck due to a faulty light setting a truck bed on fire, which was then able to be extinguished before the damage could spread. The assembly of passengers was successful without any large difficulties, with the crew performing their tasks well. In this case the crew were able to instruct the passengers about embarkation procedures (even though not necessary) and there was no panic observed among passengers.

These cases demonstrate the need for an analysis of the evacuation routes in order improve the safety of the layout itself and allow for the best possible chance for evacuation procedures to succeed. While proper LSA arrangement is important, how the evacuees will manage to utilise the available LSA must also be considered. Therefore, for a proper analysis of evacuation capabilities of a ship, behavioural simulation of the passengers is necessary.

2.1.5 Evacuation Procedures and Their Difficulties

The general procedure for ship evacuations is that once the crew decides it is necessary, the Master sounds the alarm; calling for passengers to move from wherever they are to their assigned mustering stations. The crew disperses to their assigned locations to either direct passengers to their mustering stations or instruct passengers on the procedures. While the steps taken to initiate an evacuation of a ship may seem straightforward, in reality it is quite difficult to manage with some of the main reasons for this difficulty being as follows:

- **Number of passengers.** On some cruise ships there can be upwards of 6000 passengers (such as the Oasis of the Seas with a maximum capacity of 6,360 passengers and 2,100 crew [10]), and as such it is important that the design of the ship minimises bottlenecks to the assembly and embarkation stations. With such a large number of people moving urgently at once, there is a real danger of over-congestion itself causing harm and blocking escape routes. This must be addressed in the design.
- **Passenger inexperience.** The passengers on-board a passenger ship will typically lack the experience in abandonment procedures when compared to e.g. the crew of a merchant ship. While evacuation drills are required by the IMO on journeys lasting longer than 24 hours, it is still important to design the interior in such a way that it is simple and intuitive to understand where to go in case of emergency [11], [12]. Clear signage and instructions over intercom systems, as well as crew directions are a way to alleviate this but will not eliminate the chance of passengers being lost.

- **Passenger demographics.** The average age of cruise line passengers globally in 2017 was 47 [13], meaning that there will be many with their movement impaired which will impact the speed at which they can evacuate. These demographics are important to consider when designing a safe ship, as well as in any evacuation analysis that is to be performed. These demographics will also be distributed differently depending on the time of day, and the type of ship involved.
- **Environmental factors.** One difficulty faced specifically in evacuating ships (that is not necessary to take into account when evacuating buildings) is the outside environment. As the ship will often be out at sea and in motion when the evacuation is called for, the effect of the ship listing can have a considerable effect on the ability of passengers to move about and find their way through the ship. Also, outside weather conditions can be an issue if assembly stations or embarkation stations are placed outside the hull, where the weather can be quite severe, and people may need to wait several hours for rescue.

2.2 IMO and Other Regulations

Regulations concerning evacuation and escape arrangements are mainly dictated by the IMO, with the three most relevant documents being:

- SOLAS - Chapter II-2 - Part D - Regulation 13 - Means of escape [14]
- FSS - Code Chapter 13 – Arrangement of means of escape [15]
- MSC.1/Circ.1533 - Revised guidelines on evacuation analysis for new and existing passenger ships [16]

2.2.1 Means of Escape

The means of escape regulations described in **SOLAS, Chapter II-2, Part D, Regulation 13: Means of escape** prescribe general design requirements for escape routes from various parts of the ship. These answer questions such as how many escape routes are required from each space, what direction should doors open, and where should assembly stations be located.

The most important part of the regulation with regards to this topic is as follows [14]:

> 3.2.7 *Evacuation analysis for passenger ships*
>
> 3.2.7.1 *Escape routes shall be evaluated by an evacuation analysis early in the design process. This analysis shall apply to:*
>
> .1 *ro-ro passenger ships constructed on or after 1 July 1999; and*
>
> .2 *other passenger ships constructed on or after 1 January 2020 carrying more than 36 passengers.*

3.2.7.2 *The analysis shall be used to identify and eliminate, as far as practicable, congestion which may develop during an abandonment, due to normal movement of passengers and crew along escape routes, including the possibility that crew may need to move along these routes in a direction opposite to the movement of passengers. In addition, the analysis shall be used to demonstrate that escape arrangements are sufficiently flexible to provide for the possibility that certain escape routes, assembly stations, embarkation stations or survival craft may not be available as a result of a casualty.*

The escape route design is further specified in the **FSS Code Chapter 13**, which describes how to calculate staircase dimensions (width, landing areas) with regards to the amounts of people expected to use them in emergency cases. The codes describe two cases for distributing people for the purposes of these calculations [15]:

Case 1 *Passengers in cabins with maximum berthing capacity fully occupied; members of the crew in cabins occupied to 2/3 of maximum berthing capacity; and service spaces occupied by 1/3 of the crew.*

Case 2 *Passengers in public spaces occupied to 3/4 of maximum capacity, 1/3 of the crew distributed in public spaces; service spaces occupied by 1/3 of the crew; and crew accommodation occupied by 1/3 of the crew.*

2.2.2 Evacuation Analysis

While there are extensive regulations dictating the arrangement of escape routes for passenger ships (in both SOLAS [14] and the Fire Safety Systems (FSS) Code [15]), the first form of regulation regarding evacuation analysis was only put forth by the IMO in the 1995 SOLAS Conference as SOLAS II-2/28.3 as a response to the MS Estonia disaster. It required that escape routes should be evaluated using a suitable evacuation analysis method early on in the design process in order to identify possible congestion points in the arrangement, and also demonstrating that the evacuation routes are flexible enough to allow for circumstances changing the routes available. This amendment to SOLAS applied to ships built after July 1st, 1999.

As the regulation itself is rather vague, the MSC released an interim set of guidelines on how to perform a simple evacuation analysis in its 71st session (May 1999) with MSC/Circ. 909: Interim Guidelines for a Simplified Evacuation Analysis of RoRo Passenger Ships [17]. As this set of guidelines only applied to RoRo passenger ships, the MSC requested the Fire Protection committee to develop guidelines for passenger ships in general (including high-speed craft).

From then on there have been several iterations of the SOLAS regulation regarding the analysis; and the evacuation analysis guidelines up until its current form: MSC.1/Circ. 1533: Revised Guidelines on Evacuation Analysis for New and Existing Passenger Ships. This makes evacuation analysis mandatory for all passenger ships (with more than 36 passengers) constructed on or after 1 January 2020 [16].

2.2.3 Overview of the Evacuation Analysis Guidelines

The guidelines provide two methods to perform an evacuation analysis: A simplified analysis (Annex 2) and an advanced analysis (Annex 3). Annex 1 consists of the background behind the methodologies, how to evaluate the results, the scenarios to be analysed and common assumptions in the two methods.

The ultimate goal of the two methods in the guidelines is not to provide a fully accurate representation or prediction of what would happen in case of a real emergency, but to allow an evaluation of the safety of a ship against a series of benchmark tests; some reasons for this being:

- **To ensure uniformity in application of the analysis.** As the field of evacuation simulation is ever growing with software being able to perform more and more complex calculations, the line of what is considered realistic enough can be blurred. Therefore, it is important for all ships to be held to the same standard for the evaluation to be meaningful.
- **A lack of verification data.** While the calculations may be able to depict realistic scenarios and results, there is a distinct lack of measured data of actual evacuations to verify this.
- **A lack of experience in specifically ship evacuation analysis.** Another reason to employ many of these assumptions is that the majority of the theory behind ship evacuation comes from the civil building sector. While there are many similarities in how emergency situations play out between building and passenger ship, some key differences such as ship motion limit the applicability in building evacuation models simulating realistic ship emergency scenarios.

The distinction between the simplified analysis and the advanced analysis is an important one: the simplified analysis is a single calculation of evacuation time considering the topology of the ship, without simulating the individual evacuating passengers; whereas the advanced evacuation analysis seeks to also simulate the individual people and their decision-making process. This presents a vast difference in the complexity involved and assumptions made.

While there are differences in how the analysis is carried out between the advanced and the simplified method, the end results with which they are judged are the same in both methods. According to the guidelines, the calculated evacuation time consists of three parts:

- **Response duration (R).** The time taken for the passengers to respond to the emergency (the time between the alarm sounding to the passenger moving).

- **Total travel duration (T).** The time taken for all passengers to reach their assembly stations.
- **Embarking and Launching (E+L).** The time taken to embark and launch the life craft.

In the calculation, reaction and travel durations are added together and multiplied by a safety factor (1.25), and the embarkation and launching duration overlaps these by a third of its duration. This is illustrated in Figure 2, with the equation for calculated evacuation duration being $1.25(R+T) + 2/3(E+L) \leq n$. As long as the longest calculated evacuation duration for all relevant scenarios is below the allowable maximum duration (n), and congestion levels within acceptable levels, the design is accepted. Even so, there may be areas of congestion that would be useful to identify and alleviate.

The maximum allowable evacuation duration depends on the type of ship being analysed, with n being: 60 minutes for RoRo passenger ships; 60 minutes for passenger ships other than Ro-Ro ships, with $\leq$ 3 Main Vertical Zones (MVZ); and 80 minutes for passenger ships other than Ro-Ro ships with $>$ 3 MVZ.

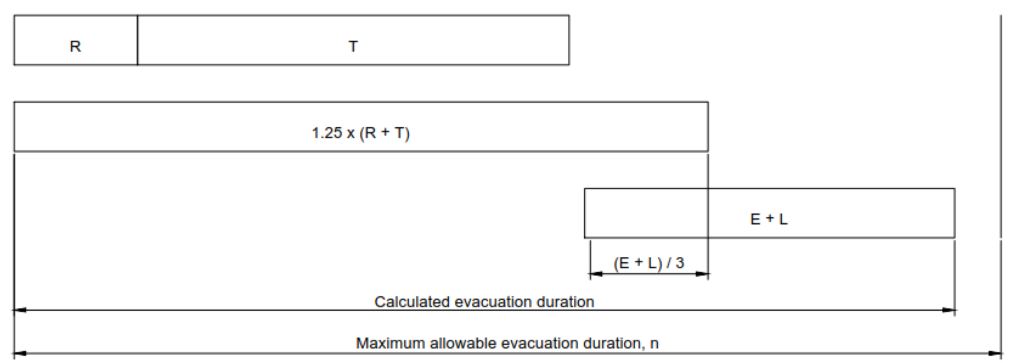


Figure 2: Definition of evacuation duration [16]

Furthermore, the analysis should be performed for a minimum of four different scenarios which are split between day and night-time scenarios [16]:

> 4.1.1 *Case 1 (primary evacuation case, night) and Case 2 (primary evacuation case, day) in accordance with chapter 13 of the FSS Code.*
>
> 4.1.2 *Case 3 (secondary evacuation cases, night) and Case 4 (secondary evacuation cases, day). In these cases only the main vertical zone, which generates the longest individual assembly duration, is further investigated. These cases utilize the same population demographics as the primary evacuation cases. The following are two alternatives*

that should be considered for both cases 3 and 4. For ro-ro passenger ships, alternative 1 should be the preferred option:

.1 *Alternative 1: one complete run of the stairways having largest capacity previously used within the identified main vertical zone is considered unavailable for the simulation; or*

.2 *Alternative 2: 50% of the persons in one of the main vertical zones neighbouring the identified main vertical zone are forced to move into the zone and to proceed to the relevant assembly station. The neighbouring zone with the largest population should be selected.*

2.2.4 Simplified Analysis

The simplified evacuation analysis specified in Annex 2 of MSC.1/Circ.1533 is a fully described method for carrying out an evacuation analysis and goes through the process step by step with examples. The aim of the guide is to provide a full method to perform an analysis that is quick to set-up and run, and is not resource intensive. The analysis treats the evacuation procedure as a hydraulic system, with passengers and crew acting as particles, and the corridors and doors acting as pipes and valves respectively.

The method assumes that all passengers and crew are distributed evenly in public spaces, and that all passengers begin the evacuation at the door of the escape route. In the case of cabins connected by a corridor, it is assumed that all passengers begin evacuation simultaneously from the corridor.

Using the population densities, the specific flow of people is calculated from a table of values for specific flow and speed, as a function of density. The specific flows for corridors, stairs and doors are also calculated from a table of values. These values can be seen in Tables A1.1-A1.3 in Appendix A1. From these, the total travel duration is taken as the longest calculated travel duration, with the reaction time assumed to be 10 minutes for the night cases and 5 minutes for the day cases. The embarkation and launching duration is assumed to be 30 minutes unless analysed further.

This method has some very significant assumptions that are made:

- It is assumed that all passengers will have the same reaction time and will proceed simultaneously to their assembly point.
- Passengers will move to their destination unimpeded, meaning that the only restrictions to their movement come from the specific flow rate of transition areas such as doors, corridors and stairs.
- Walking speed in an area is dictated by the population density of that area, and the type of area it is (corridor, stairway etc.).
- Any counter-flow movement by passengers or crew is accounted for with a correction

factor.

- The effect of ship listing or motion, or any other impeding environmental factors such as reduced visibility from smoke etc. is accounted for using a safety factor.

All of these assumptions provide a very simple method to estimate evacuation time and identify areas of congestion. The method is more suited to the early design phase, and when the ship grows in complexity, the assumptions made becomes less and less applicable. However, according to the guidelines in MSC.1/Circ.1533 paragraph 7 [16]:

> *"[I]n early design iterations of the ship, the simplified method has merit due to its relative ease of use and its ability to provide an approximation to expected evacuation performance."*

2.2.5 Advanced Analysis

The advanced analysis is a method that represents the passengers and crew as unique individuals (also called agents), with a pre-determined set of properties depending on age, gender and mobility; some of the assigned parameters are probabilistic.

Each agent is assigned to one of the population groups in the amounts shown in the population composition table (Table A2.1 in Appendix A2). Each population group is then assigned a set of attributes for walking speed in different environments as seen in Tables A2.2 and A2.3 in Appendix A2. This gives a more realistic view on how passengers will perform the evacuation as compared to dictating everyone's walking speed purely by the density of the environment, as assumed in the simplified analysis.

Reaction times are also not purely static. Instead of assuming that each agent will react to the emergency and begin movement at exactly 10 minutes, the passenger's reaction time will be determined using the following truncated logarithmic normal functions (with Equation (1) applying for the night cases, and Equation (2) applying for the day time scenarios) [16]:

$$y = \frac{1.00808}{\sqrt{2\pi}0.84(x-400)} \exp\left[-\frac{(\ln(x-400)-3.95)^2}{2\times 0.84^2}\right] \quad \text{for} \quad 400 < x < 700 \tag{1}$$

$$y = \frac{1.01875}{\sqrt{2\pi}0.94x} \exp\left[-\frac{(\ln(x)-3.44)^2}{2\times 0.94^2}\right] \quad \text{for} \quad 0 < x < 300 \tag{2}$$

Where y = probability density and x = time in seconds after the call to muster has sounded. These equations are illustrated in Figure 3.

This leads passengers to react to the emergency at different times, causing travel to their mustering stations to happen as a stream instead of a mass of people all moving at once. This means that areas that are shown as congested in a simplified analysis (where all agents are assumed to move at once) would not necessarily be congested in a more realistic scenario. As in the simplified analysis, the results of interest are the total

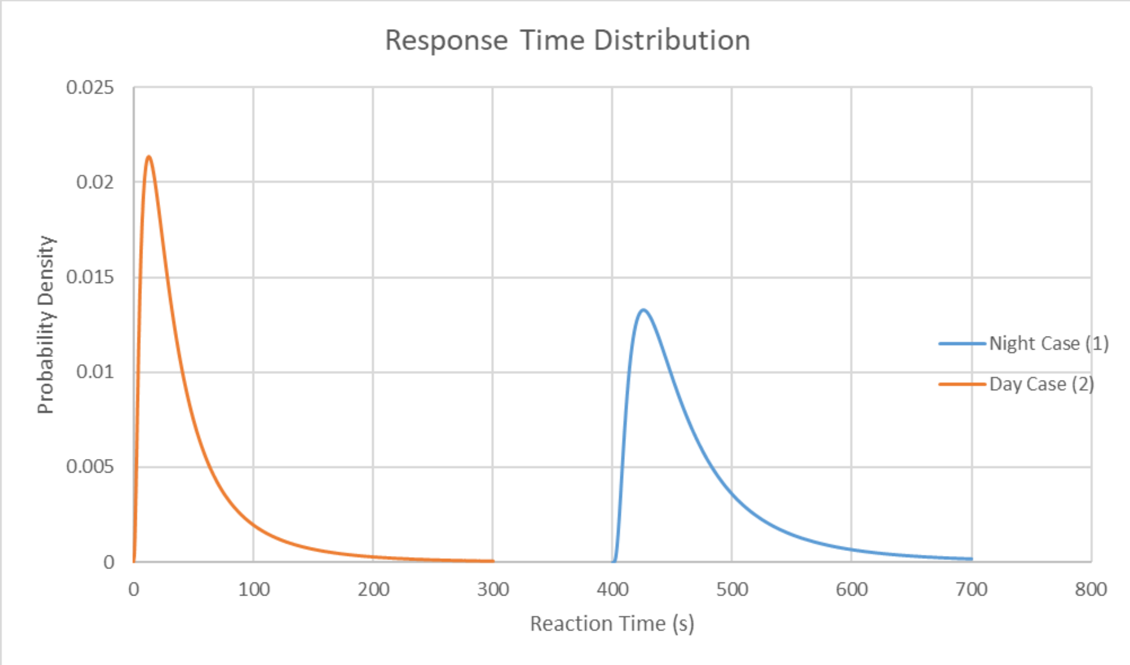


Figure 3: Response Time Distribution given in IMO Guidelines [16]

evacuation time, and the presence of any significant congestion. The total evacuation time must comply with the same requirements as before, and congestion is defined by a local population density over 4 people/m^2. It is considered significant if it lasts for longer than 10% of the total assembly duration.

As the response time is to be reassigned each time a simulation is run, as well as reassigning the positioning of the population demographics, results are given as a probability curve where the 95th percentile gives the evacuation time of interest.

The simulation is to be conducted a total minimum of 500 times, with 100 different random populations, and repeating the simulation 5 times for each population. The number of simulations can be reduced if a convergence is reached with a prescribed method [16]. The IMO guidelines also outline 12 different benchmark tests that the program must complete for validation purposes, in order to show that the model works as intended.

Not only does the advanced analysis differ in the method of analysis, the cases themselves are also slightly modified in the way they treat the crew [16]:

> 4.1 *Cases 1 and 3 (night)*
>
> *Passengers in cabins with maximum berthing capacity fully occupied; 2/3 of crew members in their cabins; of the remaining 1/3 of crew members:*
>
> .1 *50% should be initially located in service spaces;*

> .2 *25% should be located at their emergency stations and should not be explicitly modelled; and*
>
> .3 *25% should be initially located at the assembly stations and should proceed towards the most distant passenger cabin assigned to that assembly station in counterflow with evacuees; once this passenger cabin is reached, these crew are no longer considered in the simulation. The ration between the passenger and counterflow crew should be the same in each main vertical zone.*
>
> 4.2 *Cases 2 and 4 (day)*
>
> *Public spaces, as defined by SOLAS regulation II-2/3.39, will be occupied to 75% of maximum capacity of the spaces by passengers. Crew will be distributed as follows:*
>
> .1 *1/3 of the crew will be initially distributed in the crew accommodation spaces (cabins and crew day spaces);*
>
> .2 *1/3 of the crew will be initially distributed in the public spaces;*
>
> .3 *the remaining 1/3 should be distributed as follows:*
>
> .1 *50% should be located in service spaces;*
>
> .2 *25% should be located at their emergency duty locations and should not be explicitly modelled; and*
>
> .3 *25% should be initially located at the assembly stations and should proceed towards to the most distant passenger cabin assigned to that assembly station in counterflow with evacuees; once this passenger cabin is reached, these crew are no longer considered in the simulation. The ratio between the passenger and counterflow crew should be the same in each main vertical zone.*

As agents are modelled individually, counterflow should be able to be simulated and thus the correction factor for counterflow is no longer necessary.

Validation Tests

In Appendix 2 of Annex 3, the IMO guidelines [16] specify a number of test cases in order to validate the model used. There are four forms of verification that should be undertaken, and 12 defined testing scenarios:

- Component testing: 7 tests are recommended in the guidelines, each with the aim of testing that individual sub-components of the model are working as intended. These are very elementary tests that aim to test only a single feature at a time, they are as follows:

1. **Maintaining set walking speed in corridor.** One agent walking along a straight corridor at a constant walking speed.
2. **Maintaining set walking speed up staircase.** One agent walking up a staircase at a constant walking speed.
3. **Maintaining set walking speed down staircase.** One agent walking down the same staircase as in Test 2.
4. **Exit flow rate.** Several agents in a room exiting through the same door, the flow rate should not exceed the expected level.
5. **Response duration.** Several agents are assigned a response duration from a uniform distribution, each agent should start moving at the correct time.
6. **Rounding corners.** A group of agents move along a corridor with a left-hand turn.
7. **Assignment of population demographics parameters.** Assign a population of agents to a single demographic, and check that their walking speeds have been distributed properly.

- Functional verification: This verification is task specific, with the aim being to verify that all capabilities required for the intended simulation work as intended. This means that all features should be tested and documented in a comprehensible manner, with guides on the use of the features readily available in the technical documentation.
- Qualitative verification: These are tests that verify that the behaviour of simulated agents functions as expected. As some features are probabilistic, these tests are merely to verify overall traits and phenomena.

8. **Counterflow - two rooms connected via a corridor.** Two rooms that are connected with a corridor have their populations move into the opposing room simultaneously. This is done with varying numbers of people in each room, and the movement duration should increase with the amount of people.
9. **Exit flow - Crowd dissipation for a large public room.** A large room filled with people has four doors to exit. The duration it takes for the agents to exit is recorded with all doors open, and then again with all doors closed. The duration is expected to double.
10. **Exit route allocation.** A cabin area is created connected by a series of corridors, with 10 cabins being assigned main exit, and the remaining 2 cabins assigned to a secondary exit. Agents should leave through their assigned exits.
11. **Staircase.** A room filled with people should be connected to a corridor that has a staircase at the end which the people should climb. There should be

congestion forming at the mouth of the corridor as well as at the bottom of the stairs.

12. **Flow density relation.** Flow of passengers travelling through a corridor should be shown to be smaller at higher densities that at lower densities.

- Quantitative verification: This involves comparing the predictions made earlier with reliable measured data, but as there is no such data available at the moment, this is not yet required. This is again one of the main drawbacks to the validity of the advanced analysis method.

2.3 Crowd Simulation and Evacuation Behaviour

One of the most difficult aspects of modelling evacuations is in creating a way to model the decision-making process of the evacuees, as well as their subconscious actions. This has been an area of interest since the early 1950's in the design of buildings and infrastructure for the purposes of fire-safety and pedestrian flow [18].

As fire-safety is such an important aspect of architectural design, it is important to be able to predict how people will act in the face of an emergency in order to facilitate their evacuation. One way to do this is to simulate the scenario mathematically. The difficulty that arises in these studies is that people are complex and do not always make the optimal choice, but as computational methods become stronger, more aspects of the decision-making process are able to be included in the prediction models.

Trying to understand human behaviour during an evacuation is much like trying to understand the behaviour of crowds in general, with the key differences being a sense of urgency and the entire crowd trying to reach a specific location (the building exit or assembly station). Places where it would be of interest to simulate large crowds that are not in emergency situations would be e.g. shopping centers or mass-transit hubs.

One difference between modelling a single pedestrian moving from one place to another, and a large group of people doing the same is the aspect of congestion. Besides having an availability of escape routes, this is the most important aspect to consider when designing a space that is to be safe in evacuation scenarios. When a group of people move somewhere that has an obstacle causing a bottleneck (such as a tunnel, or doorway), the people at the front of the crowd risk being pressed up against the obstruction by the people behind, which can lead to fatal crushes. Examples of these in the past are:

- The Victoria Hall Disaster in 1883, where 183 children died in a concert hall in the UK when rushing down a staircase where the door at the end only opened inwards. This brought about building regulations requiring public spaces have emergency exits that opened outwards [19].
- The Hillsborough Disaster in 1989, where 95 died and over 400 were injured outside a British football stadium, due to bottlenecks in the egress points [20].
- The 1990 Mecca Tunnel Tragedy, where 1426 people died in a tunnel near Mecca, when an incident occurred at the exit of the tunnel, causing a bottleneck [21].

- The 2015 Mina Stampede, where an estimated over 2000 people died when two very large groups of people converged on the same street [22].

Crowds have therefore been studied in various ways from controlled tests to overall observations using different methods, which has led to many ways to simulate and predict the motion of said crowds.

The danger of panic is another aspect of emergency situations. In this case the definition of panic being the evacuees acting purely on the instinct of self-preservation. While panics have been shown to increase speeds, they also tend to cause people to act less rationally, become more physical and exasperate the dangers of bottlenecks [23]. A phenomenon that has also been observed is something called “Phantom panics” [23], where panic situations have occurred without any real emergency such as fire, but simply due to impatience and lack of information as to the situation at the front of the crowd. The degree to which panic occurs in emergency situations is debated as there have been very few studies on it, and as such is difficult to model.

Some phenomena in the movement of crowds that have been observed as fundamental features of crowd movement are as follows [23]:

- **Lane forming.** When two streams of pedestrians encounter, travelling in the opposite direction, they tend to naturally form lanes to facilitate fluid motion.
- **Clogging at bottlenecks.** When a large group of people try to pass through a narrow passage (such as a doorway), they tend to bunch up around the entrance, causing it to clog up. This is observed clearly when the desired velocity of the pedestrians is higher (such as in evacuation scenarios), slowing the movement of people more than if they would form an orderly queue. Further pressure is caused by people in the back not seeing the situation at the front and pushing into the crowd.

  This is also amplified when there is a group of people on the other side of the narrow passage trying to move in the opposite direction. However, it has been observed that the two crowds tend to oscillate in allowing people to move through, as when one person makes it through the passage it makes it easier for the person behind to follow. Eventually the opposing pressure grows enough for the opposing side to break through, repeating the process in the opposite direction.

  It has also been observed that this clogging can be alleviated by including another opening/doorway beside it, with a small gap in between the two. This is preferred over simply doubling the width of the passage, since the two groups tend to pick one doorway to pass through, allowing the opposing group to use the other.
- **Freezing by heating.** When the observed normal velocity of the pedestrians is high enough, opposing groups in a corridor will no longer form lanes to pass through, as each group is trying to force their way through. If the groups are similar and large enough in size, this will cause all movement to freeze entirely.

2.3.1 Cognitive and Affiliative Behaviour

When trying to model how people will make decisions, it is important to know the information available to them and what interacts with them. These can be split into two parts: their interaction with the environment (cognitive), and their interaction with other people (affiliative).

Cognitive ability is the evacuee's ability to assess the environment around them. Examples of this are their ability to acquire information on: the urgency of the situation, the best route for evacuation, and any alternative escape routes in case of crowding or blocking of the main escape route. These all play a large role in how successful they will be in evacuating, and are helped by things such as: clear and simple signage with instructions, straight corridors with good visibility, announcements over an intercom system explaining the nature of the emergency and its location. Another aspect of cognitive behaviour is the way the interior design of the ship affects the emotions of the evacuees. There have been studies on how the height of corridors affects evacuation behaviours, or how having a painting at the end of a corridor positively affects the probability of an evacuee escaping in that direction [24]. The cognitive abilities and resulting behaviour of people is important when trying to model what path a person will take in an emergency situation, and how they will move through the space.

Affiliative behaviour can be described by how people interact with and behave around other people. Examples of this is the tendency to follow the crowd (herding behaviour), following social norms such as queuing, reacting to instructions given by staff or emergency services, bonds towards family members (causing people to look for each other before heading towards the exit), and aversion of places highly congested [25], [26].

2.3.2 Experimental Methods to Study Behaviour

Besides observing the results of real accidents and disasters, human behaviour during emergencies has been researched using experiments to replicate an emergency scenario. An early example of this was an experiment run by Alexander Mintz in 1951 [18], who aimed to evaluate if people in an urgent situation were more likely to cooperate rationally, or panic and act in full self-interest but to their own detriment.

In the experiment he had a group of people pull a cone attached to a string out of a glass bottle (seen in Figure 4). The setup was designed so that only one cone would be able to exit the bottle at a time, otherwise they would jam. When there was no time limit or outside incentive, the subjects were able to cooperate and remove the cones in a timely manner. However, when a time limit or a reward/fine was introduced, it became very apparent that the cones would be congested at the bottleneck more often than not. Since then, there have been several full scale studies of people evacuating different types of location using differing means to measure the results, such as CCTV camera tracking [27]–[29] or with the use of RFID chips [29] to monitor precise movements of crowds to verify simulation models.

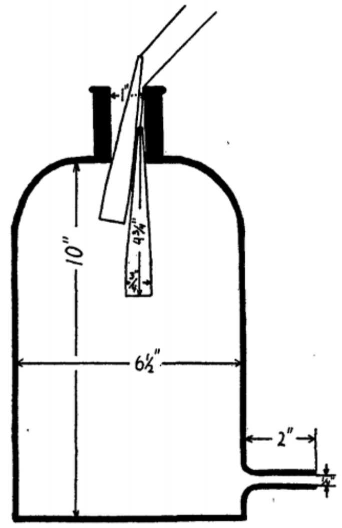


Figure 4: Illustration of the experimental setup used by Mintz [18]

2.3.3 Link to Ship Evacuations

The behavioural aspects studied in building evacuations all apply to ship evacuations as well, but there are some additional aspects to consider. These are things such as listing of the ship causing both fear and confusion, as well as being a physical obstruction to movement. In some extreme cases this listing can be quite severe, such as in Costa Concordia accident [8].

Another potential issue is an unfamiliar layout of the ship, or an unfamiliarity with the evacuation procedures. This is fortunately regulated in the sense that passenger ship journeys lasting over 24 hours must run an evacuation drill familiarising every passenger with the mustering and evacuation procedures. However, there is no requirement on when the drill must be held, and so as in the Costa Concordia disaster, the accident can happen before the drill has occurred [8]. Also, this requirement does not apply to trips lasting less than 24 hours, such as the ferry cruises operating in the Baltic, where there have been accidents with large numbers of casualties such as the MS Estonia [1]. For many passengers it may be the first time on the ship and as corridors within cabin areas tend to look very similar without a view outside the ship, they can easily be disoriented.

Another factor unique to ship evacuations, is that the decision to raise the alarm and evacuate the ship is made by the ship master. This allows for additional human errors to come into play, which plays a large effect on the success of the evacuation [30]. For instance, the inaction of the master for the Costa Concordia disaster has been identified as one of the leading reasons for the injuries and fatalities from the accident, as by the time the alarm to evacuate was raised, the ship was already listing considerably [8]. One study to monitor and reduce this human error was conducted by Akyuz in 2016 [30], where the human error probability (HEP) for each step in the abandon ship procedures for an oil tanker was calculated, with proposed measures to reduce the HEP for each step. This human error risk analysis is of great importance within the offshore industry, where accidents can have a significant impact on the global environment, and their evacuation procedures are conducted similarly to those on ships [31].

2.4 Evacuation Models

Pedestrian modelling has been of great interest to the building safety and crowd management communities for a while, and with increases in computing power and simulation methods, the demand for models to validate the safety of designs grows. Over the past few decades there have been many different ways to model evacuations which can be broken down into three main categories based on their scale: Macroscopic models, Microscopic models, and Mesoscopic models.

2.4.1 Macroscopic Models

The first attempts to model pedestrian movement was carried out in the 1950's, applying it for the calculation of Required Safe Egress Times (RSET) for buildings, continuing in the 1960's and 1970's [32]. These were done at first with simple calculations approximating the motion of people as a fluid, where each person represents a particle in that fluid. This is evident when taking a top-down view of a crowd exiting a building or stadium, lending the name to macroscopic models where each individual is just a part of one large flow.

The ultimate goal of a macroscopic model is to view the evacuation process as a hydraulic system, where the motion of crowds through corridors and doors is analogous to fluid flow through pipes and valves. The basic concept is that agents are represented as a fluid with a density and a velocity. The density is assumed to flow towards the egress points. This density changes as pedestrians flow through different types of geometry (such as a staircase or doorway), thus affecting the velocity [33].

The validity of the assumption has been studied by Moore et al. [27], where they used video capture of evacuation drills to analyse the motion of pedestrians. Their findings concluded that high-density crowds moving in a steady pace over a uniform geometry indeed move much like particles in a fluid and can be modelled as such. Other examples of the use of macroscopic modelling has been in the use of traffic flow analysis in city-planning as it is a good way of simulating and predicting high-level pathfinding, and traffic flow is rule-based and thus more predictable. However, the analogy breaks down within a more complicated environment, with different groups of people moving in different directions without a common destination.

The simplified evacuation analysis outlined in the IMO Guidelines is a macroscopic model where the relevant parameters are the geometry of doorways, stairs, corridors, and population density. While this sort of analysis is relatively simple to set up and run (it can be performed using spreadsheet calculations), the applicability of it is limited to the calculation of total evacuation time and the identification of possible bottlenecks. This is due to some limiting factors:

- As macroscopic models do not simulate individual passengers, it does not take into account different demographics of passengers having different parameters, such as walking speed.

- Also linked to not simulating individuals, the decision making aspect and other individual behaviours can not be simulated, and therefore all passengers are assumed to travel the shortest distance and at the same time. Consequently, it does not take into account agent-to-agent interactions such as lane-forming during counter flow and herd phenomena, or agent-to-environment interactions such cognitive decision making.

2.4.2 Microscopic Models

As a contrast to Macroscopic models, Microscopic models treat the simulated people as individual agents, with their own set of characteristics and behaviours. This looks at the simulation from the ground level, focusing on the interaction between the agent and the immediate environment. This can be achieved in numerous different ways, with some of the most common methods being Cellular Automata and the Social Force Model [34].

Cellular Automata

A Cellular Automata (CA) model was one of the first truly microscopic pedestrian models developed. It is based on dividing the entire geometry into discrete cells, and having each agent occupy a single one of these cells [35]. A typical size for each cell would be 0.4×0.4m with agents being unable to overlap. The status of each cell can be empty, occupied or an obstacle, and movement occurs at each discrete time step. An example of an office space modelled in AENEAS can be seen in Figure 5.

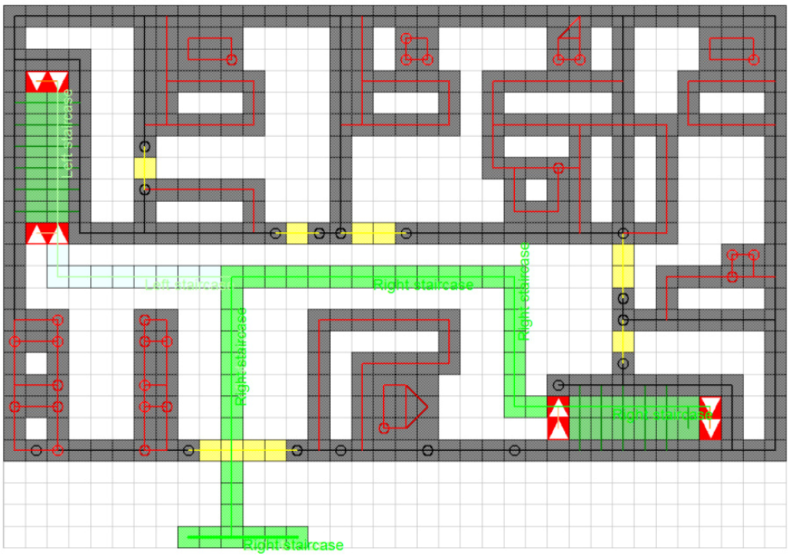


Figure 5: Example of an office space CA geometry model, built using AENEAS [36]

An example of such a CA model is one developed by S. Ha et al. [37]. In this example, path-finding is rather simple, relying on a visibility graph to plot the possible exit routes, and a Dijkstra algorithm to select to shortest one. In addition to this, human behaviour is programmed into the agents by giving them an interaction radius of three cells, where each individual agent can make decisions on where to go based on the occupation of cells around them. This allows for the programming of agent behaviour, defining behaviours for:

- **Separation.** How each agent decides to avoid collisions, and what distance to maintain from other agents.
- **Cohesion.** A preference for agents to stay in the middle of a large group.
- **Alignment.** A preference for agents to match the speed and direction of others.
- **Counter-flow.** Side-stepping in order to allow for agents moving in the opposite direction to pass, which may result in lane-forming.

At each time step, each agent evaluates nearby cells and assigns a score to them based on their: position relative to the shortest path to their goal, proximity to other agents at that time step and proximity to obstacles or hazards. Then the agent moves to the cell with the highest score available. This creates a movement simulation where each agent reacts to the environment and each other throughout the simulation. It is a straightforward method that does not require much processing power, and still allows for the programming of individual parameters to the agents [38].

However, there are some downsides to this cellular approach. Due to the way the geometry is discretised into equal sized cells, quite a lot of geometrical fidelity is lost (Figure 6). Another issue is the fact that each cell can occupy exactly one agent at a time, with no allowance for overlap. Essentially this locks the maximum population density, whereas in an actual emergency situation, people may bump into each other when travelling at high velocities, and squeeze together at crowded doorways or corridors [23]. This can be a disadvantage when congestion is one of the main variables that is to be evaluated in an evacuation analysis.

Social Force Model

The social force model relating to evacuation simulation was developed first by Helbing and Molnár [39] and is based on the idea that the environment and other agents would exert a 'social force' on an agent, either repelling or attracting them. This formulates the movement of the agent within equations of motion, where the environment affects their acceleration and deceleration indirectly; not through imparting a physical force, but rather impacting their motivation to move in a certain way. The agents are given a desired destination, to which they will take the shortest path they can at their desired speed. However, they are also able to recognise other aspects of the environment which may affect both the path and the velocity of the agent, such as obstacles or other agents. These all impart a repulsive force on the agent, which becomes stronger as they come closer, causing the agent to avoid collisions and preferring less dense (and thus possibly faster) routes. This also allows for the programming of attractive forces leading family and friends to travel together, or general herding behaviour and lane-forming.

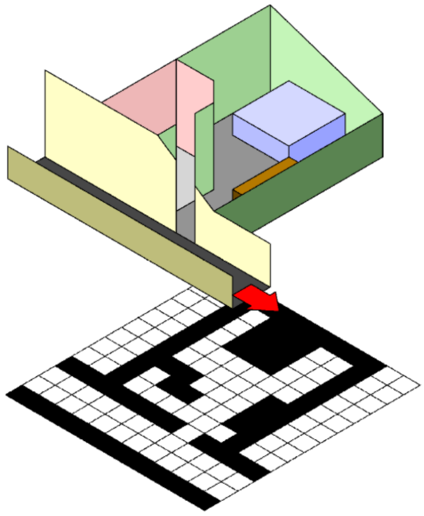


Figure 6: Discretising a 3D environment into a CA Model [36]

Physical forces impacting agents can also be implemented in this type of a model, such as frictional forces and pressures caused by high agent density, or the impact that slopes (and ship listing) have on agent motion.

A benefit of this method of modelling is that it allows for higher resolution geometries, more realistic crowd scenarios (with the possibility of demonstrating the phenomena present in high density crowds) and for more fluid motion. However, this increase in complexity for the model can significantly increase the computational power required to perform it.

An example of an application of the social force model is the pedestrian model developed by Park et al.[3] called IMEX (Intelligent Model for EXtrication simulation). This software combines two different simulation models:

- **Pynamics.** Built upon the social force model, Pynamics is a model based on Newton's laws, where passenger acceleration is determined by taking into account the passenger's self-propulsive force and all other physical and social forces affecting them. From this, the velocities, displacement and position are determined. So, similar to the social force model, this model is concerned with the repulsion and attraction of different forces on agents, but is also taking into account external accelerations and other such physical factors into the model [3].
- **PECS.** A behavioural model which determines the agent's decision-making from their: **P**hysical condition, **E**motional state, **C**ognitive capabilities, and **S**ocial status [40].

2.4.3 Mesoscopic Models

While Macroscopic models focus on the general pathfinding capabilities and flow of population on a large scale, and Microscopic models focus on the decision-making and movement of individual agents, neither system on its own is enough to accurately describe behaviours of large amounts of people over a complex structure such as a building or ship [34]. Therefore, a combination of the two is often preferable, which is termed a Mesoscopic model. The key identifying feature of Mesoscopic models is that the model uses a Macroscopic approach to generate agent paths to their desired locations, while simultaneously using a Microscopic approach for the agents to react to the environment around them [41].

As the term Mesoscopic is rather broad (attempting a balance between Micro- and Macroscopic modelling), the majority of evacuation analysis software will use some form of Mesoscopic modelling to perform the IMO advanced evacuation analysis.

2.5 Experimental Validation

One of the great obstacles to achieve more detailed and realistic evacuation simulation models is the lack of experimental validation. So far, there have been very few full-scale trials of emergency scenarios with enough data to verify any simulations, mostly due to the large costs involved. This lack of experimental data is also a large part of why advanced evacuation analyses are not yet explicitly required by the IMO. Some notable trials have been conducted by visual observation of evacuation behaviour with the use of cameras and markers during a mock evacuation. This footage was then imported into a computer and analysed in order to determine values of walking speed, reaction times and behaviour parameters [27].

The most comprehensive trial was a project funded by the EU called SAFEEGUARD, with the aim of studying full-scale evacuation drills on cruise ships and RoPax ferries at sea.

2.5.1 SAFEGUARD Project

One of the largest validation projects to ever be run on passenger ship evacuations is the SAFEGUARD project (commissioned by the EU). In it, 5 full-scale passenger trials were conducted on three different ships: A cruise ship by Royal Carribean, a RoPax ferry by Color Line and a RoPax ferry with cabins by Minoan Lines [42]. The aim of the trials was to collect data for validation and calibration purposes, with the data collected being response times, assembly times and passenger behavioural data, as well as proposing a set of validation criteria and protocols. In addition to this, an objective of the SAFEGUARD project was to propose additional benchmark scenarios for the IMO to use in certifying evacuation analysis software, including the effect of fire, trim and heel [43].

Passenger response data was collected with the use of strategically placed video cameras on-board the ships, with the objective being not only response times, but also the manner in which passengers respond to the emergency. 2366 points of response data was collected from both cabin spaces and public spaces, allowing for the generation of response time distributions for both RoPax and cruise ships [44].

Passenger assembly data was measured by noting the start and end positions of each passenger and measuring the travel time taken. The travel time data was collected using infra-red beacons placed in different locations and data logging tags worn by the passengers. This produced 3680 assembly time datapoints, contributing to the creation of two validation datasets (one for RoPax and one for cruise ships). The behavioural data from the passengers was collected using a questionnaire given to passengers after each trial was complete. The goal of the questionnaire was to give information on things that couldn't be recorded on cameras or using IR tags, namely the reasons behind making the decisions that they made.

Some of the findings that came from these trials include general characteristics of Response Time Distributions (RTD), and suggested new Passenger RTDs that fit a log-normal model. As such, these are similar to that of RTDs in the built environment and those of the IMO cases but are based on actual trials run on-board their respective ship-types [44]. The proposed RTDs suggested can be seen in Figure 7. Another result from the project was two different validation datasets for evacuation duration; one for the Royal Caribbean cruise ship, and the other for the Colorline RoPax vessel. These are publicly available datasets that can be used to validate a software model [43].

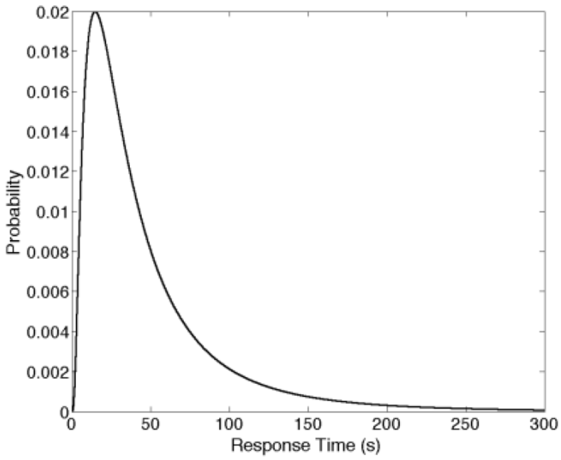
Along with the data were suggestions on criteria with which to validate a model (m) against the validation data (E). The metrics suggested are as follows [43]:

- **The Euclidian Relative Difference (ERD).** Which is used to evaluate the distance in magnitude between two curves. A result of 0 indicates both curves are identical in magnitude, and a difference in 0.1 indicates a 10% difference.

$$\frac{\|E-m\|}{\|E\|}=\frac{\sqrt{\sum_{i=1}^{n}(E_i-m_i)^2}}{\sqrt{\sum_{i=1}^{n}E_i^2}} \tag{3}$$

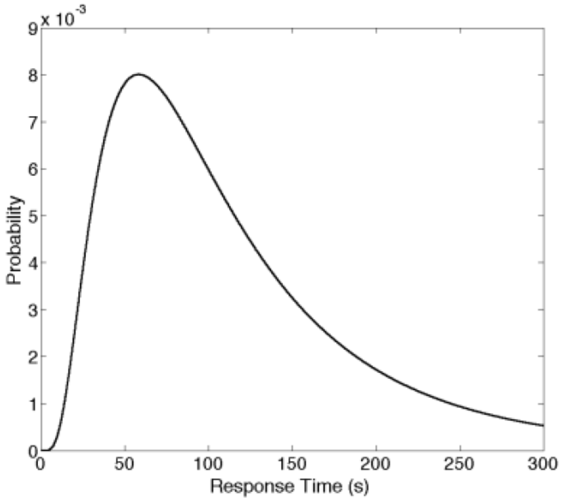
- **The Euclidian Projection Coefficient (EPC).** Which is used to evaluate the level of agreement between two curves. Here a result of 1 indicates the difference between the vectors of the two curves are as small as possible.

$$\frac{\langle E,m\rangle}{\|m\|^2}=\frac{\sum_{i=1}^{n}E_im_i}{\sum_{i=1}^{n}m_i^2} \tag{4}$$



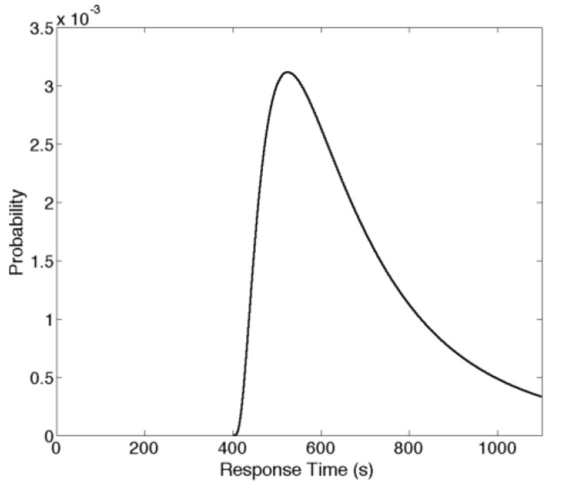
$$y = \frac{1.0076}{\sqrt{2\pi}\,0.903x}\exp\left[-\frac{(\ln(x) - 3.511)^2}{2 \times 0.903^2}\right]$$

(a) Suggested new IMO Day Case RTD for RO-PAX ferries



$$y = \frac{1.0548}{\sqrt{2\pi}\,0.702x}\exp\left[-\frac{(\ln(x) - 4.562)^2}{2 \times 0.702^2}\right]$$

(b) Suggested new IMO Day Case RTD for Cruise Ships



$$y = \frac{1.1074}{\sqrt{2\pi}\,0.817\,(x - 400)}\exp\left[-\frac{(\ln(x - 400) - 5.49)^2}{2 \times 0.817^2}\right]$$

(c) Suggested new IMO Night Case RTD for Cruise Ships

Figure 7: Suggested new RTDs from the SAFEGUARD project [44]

- **The Secant Cosine (SC).** Which is used to evaluate how well the shape of two curves match, using a smoothing term (s). A result of 1 indicates that the curves are identical in shape.

$$\frac{\langle E, m\rangle}{\|E\|\|m\|} = \frac{\sum_{i=s+1}^{n} \frac{(E_i - E_{i-s})(m_i - m_{i-s})}{s^2(t_i - t_{i-1})}}{\sum_{i=s+1}^{n} \frac{(E_i - E_{i-s})^2}{s^2(t_i - t_{i-1})} \sum_{i=s+1}^{n} \frac{(m_i - m_{i-s})^2}{s^2(t_i - t_{i-1})}} \tag{5}$$

As mentioned earlier, these metrics, as well as the percentage difference in Total Assembly Time (TAT), were proposed by the SAFEGUARD team to be used to assess the validity of an evacuation simulation against their experimental data. The proposed acceptance criteria are as follows:

- ERD less than or equal to 0.45
- EPC greater than or equal to 0.6, and less than or equal to 1.4
- SC greater than or equal to 0.6 with a smoothing ratio (s/n) less equal to 0.05
- TAT within 45%

2.6 Evacuation Software

Due to the observed importance of and increased regulations regarding evacuation analysis, there is a market need to develop software with which to perform meaningful analysis in a time-efficient manner. Therefore, most software developers that deal with evacuation analysis already use some form of Micro or Mesoscopic modelling to perform their analysis.

Three main actors in the maritime evacuation analysis market are:

- Evi developed by Safety at Sea (Brookes Bell)
- AENEAS developed by Traffgo HT, in cooperation with DNV-GL
- MaritimeEXODUS developed by FSEG in the University of Greenwich

Additionally, Pathfinder developed by Thunderhead Engineering (a software suite designed for evacuation analysis of buildings), has been modified to be able to accommodate evacuation analysis on ships with IMO specified demographic selections.

Each different software suite uses different methods to perform their modelling, and therefore may reach different results. Regardless, each software fulfils the validation criteria specified by the IMO guidelines, and are therefore at least on a cursory level able to perform the analysis.

The purpose of this study is to evaluate how they differ and what effect it has on the analysis. For the evaluation, Evi and Pathfinder have been chosen for further detailed comparison, but a brief overview of the other software suites mentioned will be provided in the following section.

2.6.1 Evi

Evi is a mesoscopic evacuation analysis software initially developed by Ship Stability Research Centre at the Universities of Glasgow and Strathclyde, and further developed by Safety at Sea (which is now merged with Brookes Bell) in response to new IMO regulations requiring evacuation analyses for RoRo ships [45].

Evi is a software package that is able to perform evacuation analyses in accordance to the advanced analysis outlined in MSC/Circ. 1533, and is also flexible enough to be used in order to help validate alternative designs such as embarkation and launching simulations. The whole evacuation procedure can be visualised in a fully rendered 3D environment to help easily identify points of congestion, as well as outputting log files of relevant data. Evi evaluates the success of an evacuation by defining an "Evacuability Index" for the ship [41]. This index is one created specifically for this programme, and is defined as a function of:

$$E = f\{env\,,\, d\,,\, r(t)\,,\, s(n_i)\,;\, t\} \tag{6}$$

Where

env	=	The environment of the ship, meaning the topology and geometry of the ship.
d	=	The distribution and location of passengers on board.
$r(t)$	=	The reaction time of the passengers on board (including perception to cues and interpretation of instructions).
$s(n_i)$	=	The walking speed of individuals.

This is thus meant to define the probability of fully evacuating a given environment within a particular scenario. To produce a probability density function, each scenario is calculated multiple times to produce something like Figure 8.

Geometry

The geometry is made up of individual regions defined as either cabins, corridors or public spaces. These regions are then connected by gates which constitute different types of doors and openings. The ship is modelled one deck at a time to then be connected by stairway regions. Unlike in a CA model, the geometry is not divided into discrete cells, but is considered a continuous environment that is then meshed out to provide the model.

Agent Modelling

As Evi makes use of a Mesoscopic modelling philosophy, agent modelling is essentially split into two components: A Macroscopic model and a Microscopic model.

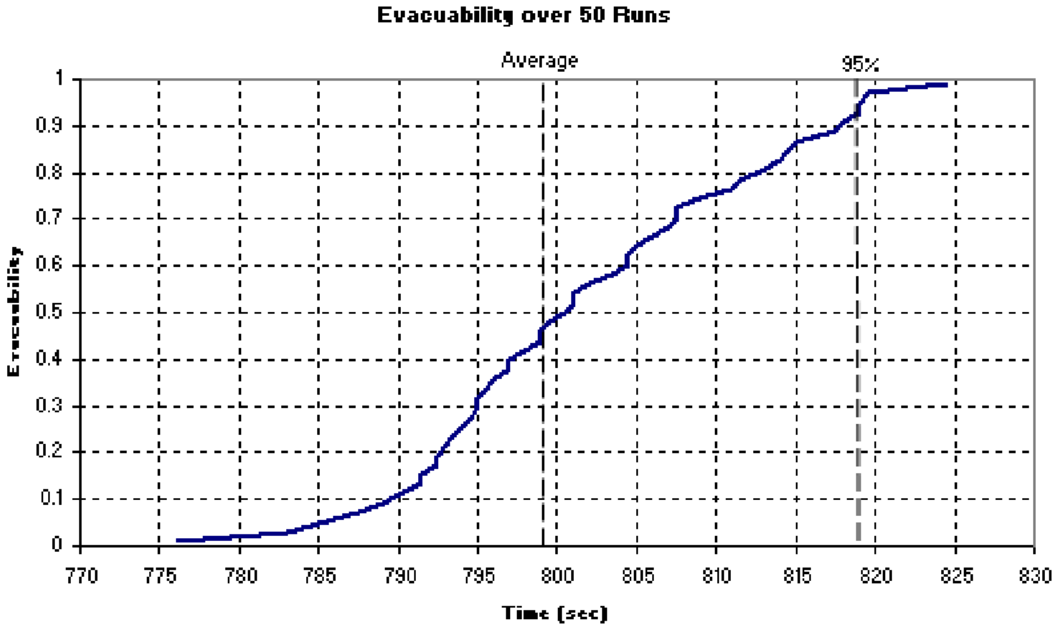


Figure 8: Evacuability index of a ship [41]

The Macroscopic model is mainly concerned with finding the overall route that the agent will traverse to their destination, and as such can be represented with a graphical view of the topological relationship between spaces and doors. As the movement within the spaces is dictated by the Microscopic model, the graph can be simplified to a schematic representation of how doors are connected to each other and their distance.

The Microscopic model is used to navigate within the room they are currently in, and focuses on reaching the entrance to the next room within the macroscopic pathfinding. The behaviour and movement model is based on the social force model mentioned earlier, determining how agents interact with their environment, with parameters defining agent perception levels such as field of view to determine collision avoidance and route choice.

2.6.2 Pathfinder

Pathfinder by Thunderhead Engineering is another Mesoscopic evacuation analysis software specifically designed for analysing building evacuation. It is a multi-agent simulation software that runs the simulation in a fully rendered 3D environment, and it has been modified to be able to include the response times and population demographics specified by the IMO in its night and day scenarios [46].

Geometry

The geometry of the space is rendered in a fully 3D environment, from which a 2D navigation mesh is created over the surfaces which agents will travel on. This allows for automatic imports of environments from certain other file formats over which the mesh

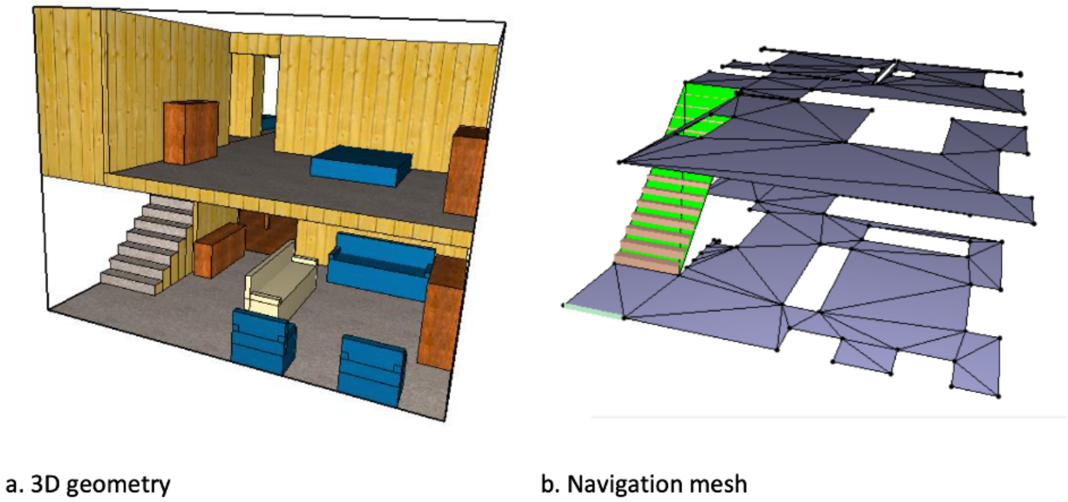


Figure 9: Pathfinder geometry [46]

will generate the environment relevant for the simulation (considering any obstacles as blanks in the navigational mesh). This difference between 3D geometry and navigation mesh is demonstrated in Figure 9.

As with Evi, the geometry is subdivided into rooms that are connected by doors, and levels at different heights are connected by stairs or ramps.

Agent Modelling

Each agent in the simulation is modelled individually and given an occupant profile depending on the demographic assigned, and a goal based on their location (in this instance the preferred muster station). The philosophy behind the path planning algorithm is a "locally quickest" approach, where each agent will assess the doors in the current room and how long the queue for them is, and the travel duration to their final goal from each door (assuming there are no further obstacles). This assumes the agents have knowledge of the entire geometry at a Macro level, as well as the information of the room they are currently in. Once a door or direction has been chosen, the A* search algorithm creates a jagged path that is smoothed and reduced to a series of waypoints where the direction changes. These waypoints are then followed in a smooth motion until the goal is reached, or the goal has changed due to a reassessment of the current room.

The motion itself can be implemented in two modes:

- **SFPE Mode.** This mode follows the guidelines given in the Society of Fire Protection Engineer's (SFPE) Handbook of Fire Protection Engineering [47]. This method determines agent speed in rooms by occupant density, and flow through doors by door width. The data from this handbook is also used in the IMO guidelines for the simplified analysis.
- **Steering Mode.** This mode creates a set of directions an agent can move and

scores them using a weighted sum of a set of defined steering behaviours. These steering behaviours are things such as maintaining the current path, avoiding other agents and obstacles, preferring less dense paths, forming lanes in counterflow situations, trying to stay behind agents that walk faster or turning around corners as a group without cutting other agents off. This all is used to give a score to a particular direction, and the velocity and acceleration needed to take that action is calculated. This all results in more complex behaviour and movement.

Due to Pathfinder being intended to analyse more than maritime evacuations, there are also features for simulating vehicles, elevators and escalators.

2.6.3 Other Software

AENEAS

AENEAS is a CA modelling tool based on Traffgo HT's previous software package PedGo which is designed for building evacuation analysis on the basis of the BYPASS project [38]. The programme is split into three separate executable files: the editor, the simulator and the viewer [36]. The editor is where the geometry is created and agents are modelled. The file created by the editor is then opened with the simulator executable, which is used to run the simulations. As the simulation is stochastic, it can be configured to run the 5 x 100 simulations required by the IMO guidelines, and the results of these runs are collated and analysed statistically. The viewer is then used to visualise and analyse the results. Playback visualisation is shown with a 3D model, with options for heat-maps. Also available are various graphical representations of the results for easier analysis.

The geometry created in the editor is discretised into a grid of 0.4m x 0.4m squares, where the outlines of the interior of the ship are defined. Walls, doors, stairs and exits all have their own cell type, and are defined individually (at the same 0.4m x 0.4m resolution). Once the overall geometry is in place, escape routes from each space must be defined, which affects the scoring of cells along the route.

Additionally, hazards (such as flooding or fire) can be defined separately, which agents will attempt to avoid by using defined alternative routes. Escape routes that the agents are to follow are defined within the geometry, as well as the desired number of agents to populate each space. A CAD file can be imported and overlaid onto the grid (at a low resolution) to aid in the processes of defining the topology of the ship. The modelling is performed entirely on separate 2D planes that are connected by stairways.

The agents themselves are considered to occupy the space of one cell and can not enter cells with a wall or another agent. As mentioned, this is a CA model and so the movement of agents is dependent on assigning probability scores to surrounding cells which determines where the agent will move. There are several parameters assigned to agents that influence the probability of moving to a particular cell, as well as taking into account surrounding features such as clustering or inertia. If an agent moves faster than 1 cell/second, they are considered to occupy both the cell they are moving to as well as the cell they moved from.

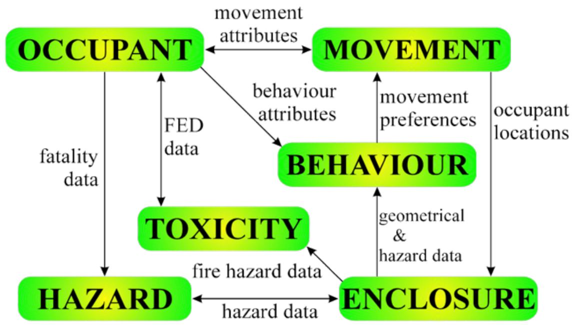


Figure 10: Submodels of MaritimeEXODUS [48]

MaritimeEXODUS

MaritimeEXODUS is another Mesoscopic evacuation modelling software, developed by the Fire Safety Engineering Group in the University of Greenwich [48]. It generates a mesh over a 2D space used to define the ship environment, connecting different decks with stairways. To model the scenario, five separate submodels are used to run the analysis, these being the Passenger, Movement, Behaviour, Toxicity and Hazard models.

The first three submodels dictate how agents will move and behave within the analysis; whereas the final two submodels dictate the damage and spread of hazards such as toxic gases and fire. MaritimeEXODUS can be run simultaneously with FSEG's other software suite SMARTFIRE, which is used to generate a CFD model of fire spread.

The geometry of the model is divided into a mesh of nodes on 2D planes, which are linked by arcs that determine the space that agents occupy. Multiple floors are connected by stairways, and can be imported from a CAD model. This whole model can then be represented by a 3D visualisation once the simulation is run.

The simulation is based on the submodels mentioned earlier and outlined in Figure 10. Each agent moves from node to node determined earlier in the geometry mesh, with the movement model determining where the most suitable node to move to is. This is what determines movements such as sidestepping, overtaking or waiting. The behaviour model determines how agents will react to the environment around them based on attributes assigned to them in the occupant model. The occupant model also determines things such as age, gender, maximum speed and reaction time. These attributes can be affected by other models.

In contrast to the other software, MaritimeEXODUS also includes hazard and toxicity models, which are used to simulate the effects of fire on-board, as well as the effect of smoke on fleeing agents.

3 Research Methodology

3.1 Software Selection

As previously mentioned, there are several different advanced evacuation analysis software on the market, all using different methods, offering different user experiences and completing the analysis task to different degrees. In order to evaluate them, a set of criteria must be established that compare both the results obtained as well as the user experience. The software that will be compared in this evaluation are Pathfinder and Evi.

3.2 Evaluation Criteria

When performing an evacuation analysis of a ship design (particularly a new-build), different stakeholders prioritise different aspects of the project. In the case of the ship owner/operator, the main priority will be the safety level of the ship, and that it complies with all regulations. For the shipyard, the main priority will be that the results allow for an economical design, and that the analysis is done at a low cost. Finally, for the designer (the end-user of the software), the main priority will be that the analysis can be completed in a time efficient manner, and that the results will be accurate and easy to display and report. As the designer is the main beneficiary of the analysis software, their interests will be focused on in this evaluation. Therefore, the criteria to be evaluated will be as in Table 1.

Table 1: Evaluation criteria

Numerical Results	The accuracy and legibility of the results are important when validating the outcome of the analysis. This will show if the modelling method has any real effect on the outcome.
Comparison with simplified method	The software will be compared with the results obtained from performing the same analysis using the simplified method, in order to investigate just how much of an improvement is made by using a more advanced method.
Setup time	The time taken to create the environment of the analysis and set up all the necessary parameters. This is the main time sink for the designer, and therefore the source of the highest cost for the analysis.
Processing speed	The time taken to run the calculations is relevant as when performing an advanced analysis, a minimum of 500 calculations must be performed. If the software is too heavy on the processor, this can be a considerable time sink.
User experience	Finally, the user interface of the software is an important aspect for the designer, as it can determine how intuitive the software is to both learn and use. This also has a considerable effect on the time taken to perform the task.

3.3 Method of Evaluation

To evaluate the software with regards to the aforementioned criteria, the same scenario must be modelled in each. For this evaluation, one Main Vertical Zone (MVZ) of a RoPax ferry will be modelled in each software, with the IMO prescribed Case 1 (Night Case) scenario. The scenario is defined in Chapter 13 of the FSS code as follows [15]:

> *Case 1: Passengers in cabins with maximum berthing capacity fully occupied; members of the crew in cabins occupied to 2/3 of maximum berthing capacity; and service spaces occupied by 1/3 of the crew.*

This also determines the formula used for calculating the reaction time of the passengers. Furthermore, the guidelines state that for the night cases, 2/3 of crew members should be located in their cabins, and of the remaining 1/3 crew [16]: *"25% should be initially located at the assembly stations and should proceed towards the most distant passenger cabin assigned to that assembly station in counterflow with evacuees."* However, crew distribution and tasks will not be taken into account in this evaluation, as only one MVZ will be modelled, within which there are no crew cabins.

3.3.1 The Ship Model

The ship itself is a 222.5m long, 63,000 GT RoPax cruise ferry that is designed to carry approximately 3000 passengers and crew. A snapshot of the general arrangement can be seen in Appendix A3.

The MVZ chosen was the second MVZ from the aft, where all passengers have their primary escape path using the same staircase. The only exception to this is the cabins on deck 5, where the cabins are located on the sides with the car deck in between. These areas have their own emergency staircase leading to the assembly stations through the outside deck.

Passenger accommodation cabins are located on decks 5-8. Decks above this only include public and service spaces which would only be including the occasional crew member in the scenario being investigated, and as such are omitted from the model.

The total number of cabins comes to 200 x 4 person cabins, and 7 x 2 person cabins, giving a total passenger count of 814. In total, there are 4 assembly stations servicing these cabins: A, B, C and D. They are located on decks 6 and 7, and double as the embarkation decks of the vessel. Service rooms such as storage spaces, laundry rooms and AC rooms were omitted from the model. As the entirety of the ship is not simulated, the final passenger density of the assembly stations will not feature in the results of the analysis.

3.3.2 Evaluation of Numerical Results

The numerical results that are to be evaluated are given as outputs for the simulations, and while every aspect of the analysis can be used, the main points of interest are as in

Table 2.

Table 2: Numerical results of interest

Demographics	These will outline differences in the approach to assigning attributes to agents as the population counts are the same.
Reaction times	
Congestion time	These three parameters illustrate agent behaviour within the model, and how their behaviour models are affected by congestion.
Travel time	
Travel speed	
Travel distance	This will outline differences in the pathfinding capabilities of agents, as the geometry is identical.
Completion time	As the main result that is sought after from the analysis, this will give an overall evaluation to the differences in the software.

Beyond a mere observational comparison of the results, the datasets created by the simulations were further compared against each other using the set of metrics outlined by the SAFEGUARD project mentioned in Section 2.5.1: The Euclidian Relative Difference (ERD), the Euclidian Projection Coefficient (EPC) and the Secant Cosine (SC). These metrics, as well as the percentage difference in total assembly time (TAT), were proposed by the SAFEGUARD team to be used to assess the validity of an evacuation simulation against their experimental data. The proposed acceptance criteria are as follows:

- ERD less than or equal to 0.45
- EPC greater than or equal to 0.6, and less than or equal to 1.4
- SC greater than or equal to 0.6 with a smoothing ratio (s/n) less equal to 0.05
- TAT within 45%

While these were originally designed for comparing a simulation dataset with the experimental dataset that resulted from the SAFEGUARD project, in this case they will be used to compare both models with each other by using the validation software developed by the SAFEGUARD team at Fire Safety Engineering Group in the University of Greenwich [49].

3.3.3 User Experience Evaluation

The setup time and processing speed criteria both fall under the user experience evaluation umbrella, as they are both integral parts of the designer's experience in using the software. As such, the time it took to complete the modelling was measured. However, since the modelling was carried out by a relative novice at both pieces of software, this observation is only used to provide general comments on the ease of use, ease of learning and user interface experience. As the modelling process alone is what is being evaluated, the time taken to prepare and design the passenger and crew distribution is not taken into account, as that can be considered part of the escape way design, rather than the evacuation analysis.

Similarly, the time it took to run the simulations themselves was also measured, as it plays a large role in the total time taken for the whole process. These results are comparable with each other as they were performed on the same computer but might not be replicable on a computer with greater processing power and such the results will only be used comparatively.

Finally, the user experience of the software itself will be compared. This evaluation will be a purely subjective view on how pleasant and intuitive the software was to use from a designer's viewpoint. As these are the views of the author alone, they are not to be taken as objective fact, or provide any final assessment (either negative or positive). However, they may offer some further insight as to how the different software packages differ and what they have prioritised in the software design.

4 Results and Discussion

The results and discussion of this study are split into two main components: The numerical results, where the simulation outcomes are analysed with comparison to the simplified analysis; and the user experience where the author's subjective view on the analysis process is laid out, including the set-up and simulation times for both Evi and Pathfinder.

4.1 Numerical Results

4.1.1 Demographics and Reaction Times

The way that the population demographics were distributed can be seen in Table 3 with both percentage and nominal populations in each demographic, in comparison to the value provided in the IMO guidelines [16].

Table 3: Distribution of population demographics

Population	Distribution as %			Nominal Distribution		
Demographics	Evi	Pathfinder	IMO	Evi	Pathfinder	IMO
Female <30	6.88 %	7.00 %	7 %	56	57	56.98
Female 30-50	7.00 %	7.00 %	7 %	57	57	56.98
Female >50	16.09 %	16.22 %	16 %	131	132	130.24
Female >50 MI(1)	9.95 %	9.95 %	10 %	81	81	81.4
Female >50 MI(2)	10.07 %	9.95 %	10 %	82	81	81.4
Male <30	6.88 %	7.00 %	7 %	56	57	56.98
Male 30-50	7.00 %	7.00 %	7 %	57	57	56.98
Male >50	16.09 %	15.97 %	16 %	131	130	130.24
Male >50 MI(1)	9.95 %	9.95 %	10 %	81	81	81.4
Male >50 MI(2)	10.07 %	9.95 %	10 %	82	81	81.4
Total	100.00 %	100.00 %	100.00 %	814	814	814.00

There are very minor variations in the population distribution between the software and the values given by the IMO, mostly due to rounding as the number of people within a single demographics must naturally be a whole number.

The reaction times in both software packages can be found in Figure 11. As can be seen, the reaction times measured in Evi follow the nominal IMO prescribed times very closely. However, the reaction times in the Pathfinder simulation are much more linear. This may be due to differences in how the reaction times are assigned to agents within the simulation, or because of user-error as they had to be manually inserted and modelled when setting up the simulation. Unlike in Evi, Pathfinder does not have the IMO cases built into the software.

4.1.2 Congestion and Travel Statistics

Overall, the Pathfinder simulation experienced much less congestion (m=3.99s) compared to Evi (m=22.18s), leading to lower travel duration (Figure 12). The most congested

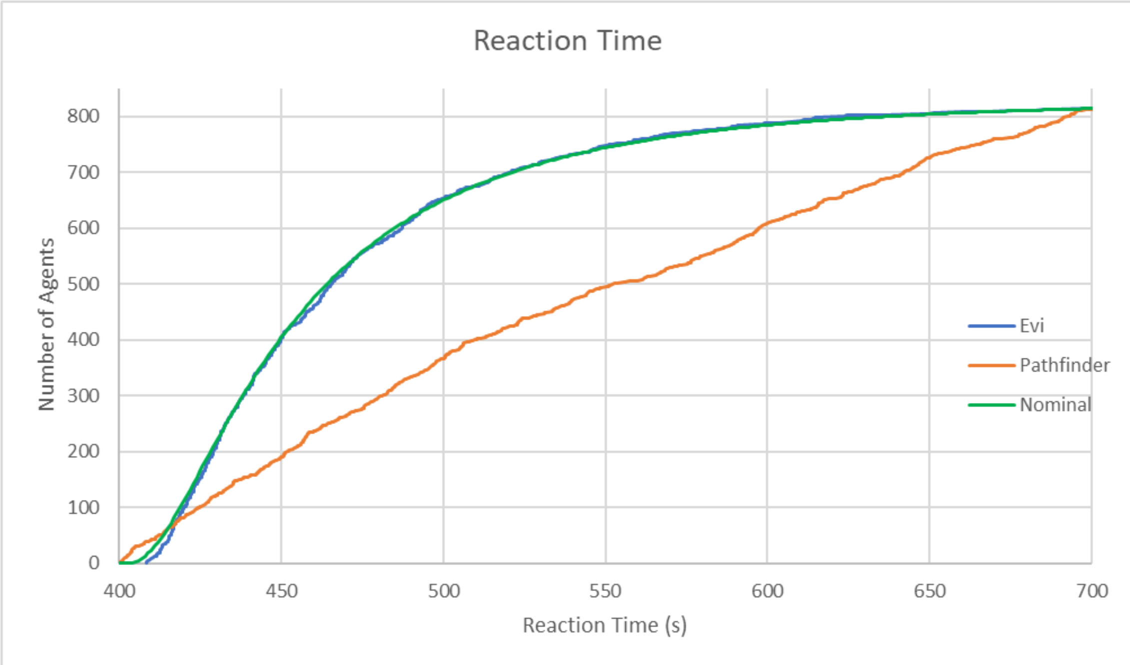
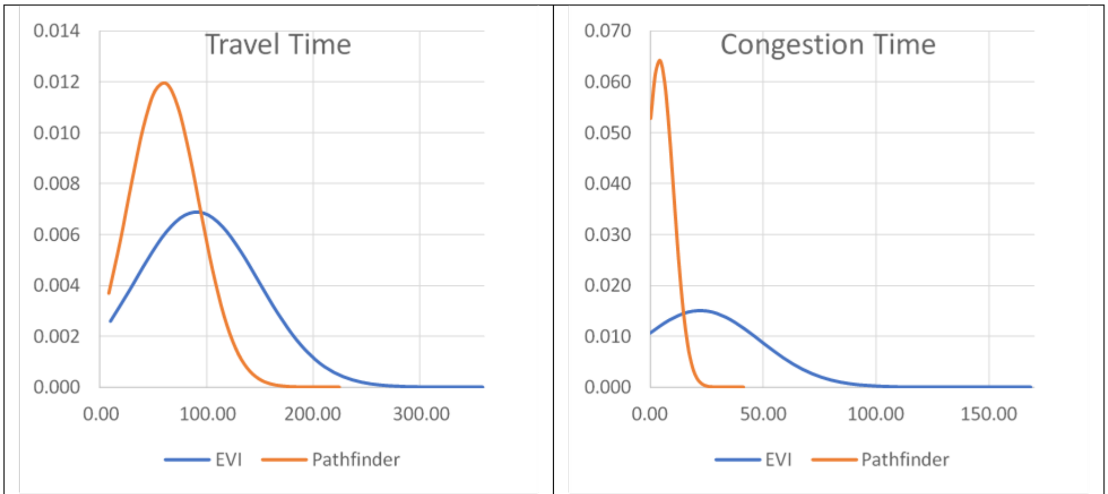


Figure 11: Observed reaction times in Evi and Pathfinder, compared to the IMO case



Results	Evi	Pathfinder	Results	Evi	Pathfinder
Max	359.00	224.38	Max	168.50	41.35
Min	10.00	8.50	Min	0.00	0.10
Mean	90.87	59.63	Mean	22.18	3.99
SD	57.84	33.31	SD	26.55	6.21

Figure 12: Probability density fucntions of observed travel and congestion times

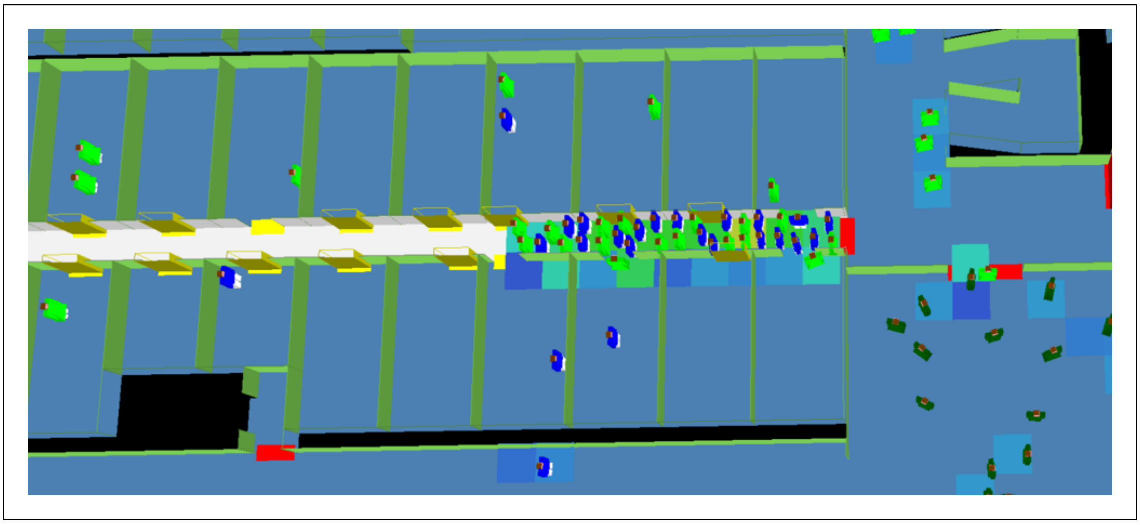


Figure 13: Demonstration of a congested corridor in Evi

area in the Evi simulation was one cabin corridor on deck 6, illustrated in Figure 13. This may be due to the differences in reaction time, with the Pathfinder agents reacting in a more linear distribution, allowing for a smoother flow of agents through corridors, whereas Evi has a clear spike in reaction times early on causing congestion. However, this difference in congestion is quite insignificant as the congestion duration is so small within this scenario.

While the speeds all fell within the limits defined by the IMO guidelines [16], unfortunately, the travel speeds for Pathfinder were each occupant's assigned maximum speed, whereas the speeds given by Evi were an average calculated from their travel distance and travel time (Figure 14). Therefore these will not be used for further comparison.

That being said, the distance travelled appeared shorter for the Evi simulation (m=30.04m) than in the Pathfinder simulation (m=64.20m) (Figure 15). This could be due to differences in the path-finding algorithm. Another possibility is that in Pathfinder, once reaching their muster station agents will still tend to move about in order keep some personal space as more people enter the station. This may be affecting the distance travelled measurement.

4.1.3 Completion Time

In the end, the completion times for both software packages are fairly similar (Figure 16). With only a 2% variation in average completion time and 9.08% variation in maximum completion time, the ERD of the samples is 0.107574. This indicates that the average distance between the two model's datapoints is only 10.8% ($<$45% suggested limit). Also, the EPC is 1.068367, indicating that the difference between the model's vectors are incredibly small (suggested criteria $= 0.6 \leq$ EPC ≤ 1.4). Finally the secant cosine with a smoothing term of 0.005 is 0.898765 showing that the average shape of the two datasets is also very close ($>$0.6 suggested limit). With this in mind, it is clear that despite their slight differences, the two simulation models perform similarly, and provide similar results

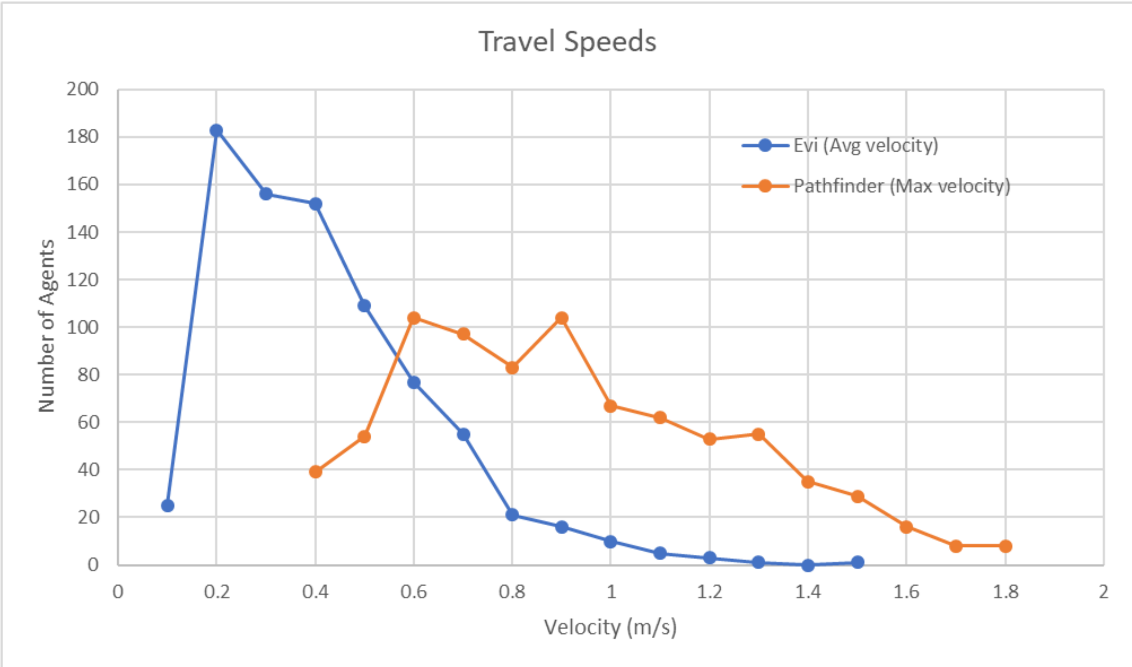
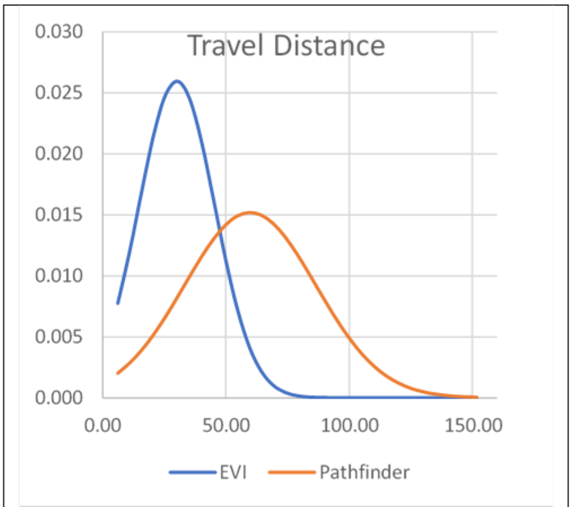


Figure 14: Distribution of travel speeds



Results	Evi	Pathfinder
Max	151.62	154.70
Min	6.10	11.30
Mean	30.04	64.20
SD	15.39	26.30

Figure 15: Probability density function of observed travel distances

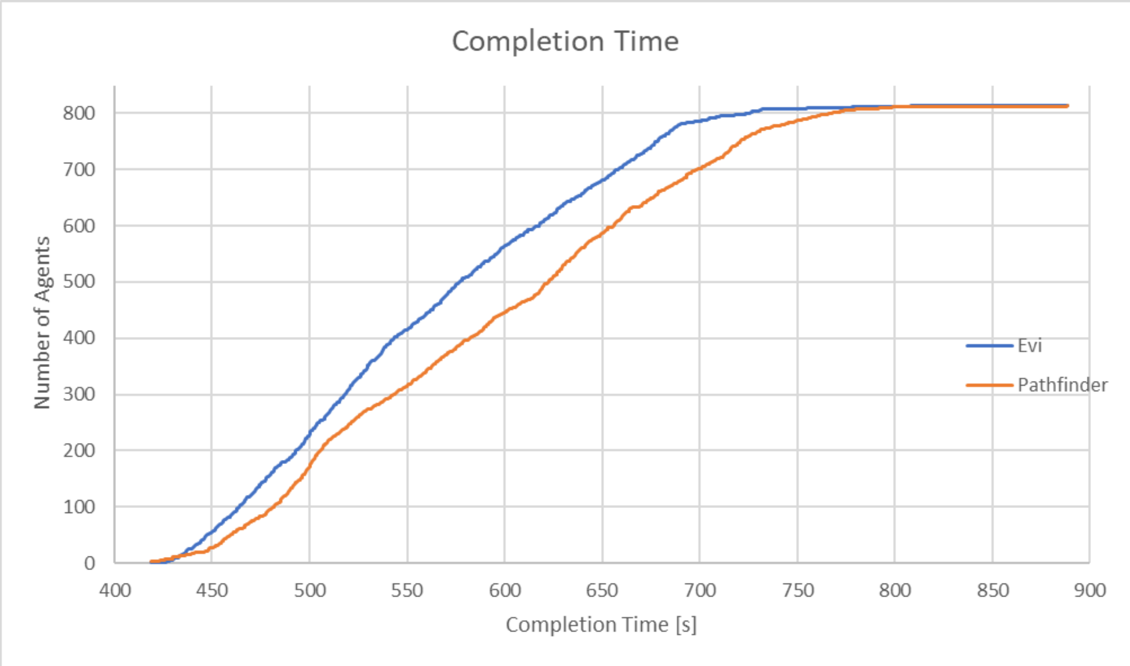


Figure 16: Measured completion times of a single run with both Evi and Pathfinder

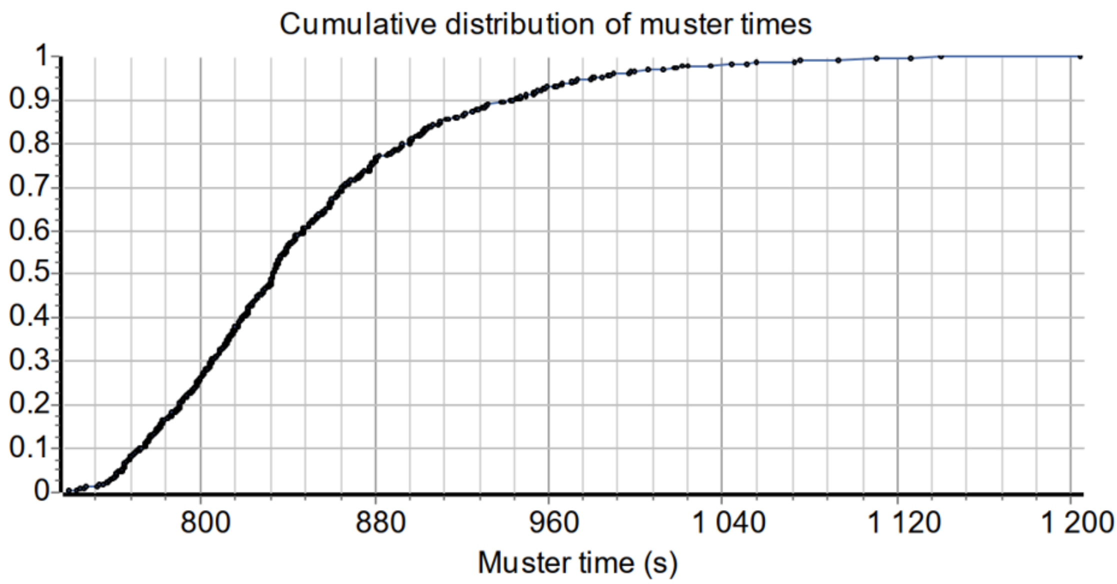


Figure 17: Cumulative distribution of muster times over 500 simulations with Evi

falling within the suggested validation criteria.

Furthermore, the Evi simulation was run for the IMO prescribed batch of 500 runs (Figure 17). From these, the average maximum completion time was calculated as 847.09 seconds, and the 95th percentile as 1204.5 seconds. This shows that while the two software performed similarly for this single run, the full batch would need to be run in order to gain a more complete picture, as the results are probabilistic. The full results of the batch run are shown in Appendix A4.

Further validation could be done by comparing both simulation models with the SAFE-GUARD Validation Dataset (SGVDS1), which is the data obtained from the SAFEGUARD project, measuring a full-scale evacuation exercise on a RoPax ferry. The test performed in this study can not be directly compared to the dataset as the SAFEGUARD experiment was run during the daytime with a population of 480 passengers on a much smaller ship, and as such is too different of a scenario. However, running a simulation of the same evacuation scenario as that run during the SAFEGUARD trials would be of interest for the future.

4.1.4 Simplified Analysis

As another point of comparison, the simplified evacuation analysis of the same area was evaluated. The analysis itself was performed using a spreadsheet tool following the steps outlined by the IMO guidelines. While the use of this tool is less complex of a calculation to process, it is still quite labour intensive to set up. It requires going through the ship layout and labelling all the doors, corridors and stairs, and taking note of relevant measures of width and length. These labels are then schematised into a flow chart to allow for easy reading. Then a spreadsheet is created calculating the flows going in and out of each component of the system, to allow for the final calculation of the evacuation duration. The analysis is set up so that it analyses each main staircase individually, and as the MVZ in question contains only one staircase, the primary evacuation case of the MVZ can be considered a contained system, allowing for easier comparison. Shown in Figure 18 is a snapshot of the total evacuation duration obtained using the simplified analysis.

As the assembly stations are not all on the embarkation decks, the travel time from the assembly stations to the life-boats and MES stations is also considered in this analysis, as well as the prescribed 30min Embarkation + Launching (E+L) duration. As travel from other assembly stations as well as the E+L durations are not considered in the Evi and Pathfinder simulation, for this evaluation, only the reaction time (R) and evacuation time (T) will be considered. This gives a total time considered of **852.54 seconds (=14 min 12.54 sec)**, with the longest duration originating from Deck 8.

Comparing these results to the completion times obtained by Evi and Pathfinder, the final result lands squarely in the middle of both advanced simulation methods (5.22% larger than then maximum time for Evi, and 4.24% smaller than the maximum time for Pathfinder). This shows that there is validity in the simplified method. However, as mentioned before, it is limited in use as a design tool for laying out things such as

Calculation of T

ST2.1

Deck	t(f)	t(deck)	t(stair)	t(assembly)	t(l)	T [sec]
10	116,13	24,33	0,00	0,00	140,46	323,06
9	116,13	11,30	11,31	0,00	138,75	319,11
8	116,13	29,36	7,78	0,00	153,28	352,54
7	116,13	29,52	0,00	0,00	145,66	335,01
6	116,13	32,29	0,00	0,00	148,42	341,37

Total evacuation time					
R	600	sec			
T	352,54	sec			
E+L	1800	sec			
Embarkation time	856,83	sec			
Evacuation & launching duration		2962	sec	=1,25*(R+T)+2/3*(E+L)	
		0:49:22	min	<60 min	OK

Figure 18: The results of the simplified analysis for MVZ 2

public spaces, landing areas or corridors, as it approximates them either by their main dimensions or as pure sources of evacuees. An advanced simulation model could be used to analyse the design of public space layouts, corridor shapes, or embarkation routes in a much more valuable way. Another thing to consider when choosing whether to use a simplified analysis or advanced analysis tool is that as the complexity of the ship grows, the more difficult it is to generate a simplified analysis relative to an advanced analysis tool where the geometry is imported from other sources.

4.2 User Experience

This section first has an overview of the user experience of Pathfinder and Evi separately, followed by a synthesis of the findings. Both software sections are further divided into three areas of the process: modelling the geometry, modelling the agents and setting up and running the simulations themselves.

4.2.1 Pathfinder

Modelling the Geometry

One of the main benefits of using Pathfinder was the feature rich modelling tools available to model the topography of the space. Full .dxf files of the decks from the General Arrangement (GA) could be imported and placed atop one another. The drawing tools were very intuitive if already familiar with other CAD software, with fleshed out features such as arraying and mirroring, along with the ability to model complex polygonal shapes. These combined with the ability to snap to the underlying GA meant that the geometry modelling was quite efficient. In total, importing the decks from the GA and modelling the spaces took **10h 29min**.

Modelling the Agents

While Pathfinder had the IMO recommended agent behaviour models already installed, the reaction times were not defined. The in-built tool did not allow for a straight implementation of the equation outlined in the IMO guidelines which might explain the discrepancy in reaction times observed in the numerical results. Also, the agent models had to be placed separately in each individual cabin, and there was no way to place agents to entire cabin areas at once. In total, this process took **2h 59min** to complete.

Setting up and Running the Simulations

While Pathfinder generates the environment to great accuracy and fidelity, this results in the processing power to run the simulations being relatively high. The simulation itself ended up taking a total of 122 seconds for a single run, which is an issue because the IMO guidelines (Annex 3, section 5.3 [16]) require the simulations to *"be made up of at least 100 different randomly generated populations"* and that the *"[s]imulations based on each of these different populations should be repeated at least 5 times"*. In its current state, Pathfinder does not have any in-built method of setting up simulation batches. This means that the profile distributions among agents must be manually reset and re-entered, and the agent locations within spaces must be manually randomised. This is further exasperated by the inability to use scripting functions to run the simulations. Extrapolating this time for the required 500 runs to meet the IMO requirements would take **16h 58min** to run. This time could be slightly decreased with a more powerful computer, or with a lower resolution geometry.

The rules do allow for a reduction in the amount of simulations performed if a convergence in results can be reached using an appropriate method. One such method is outlined in the IMO guidelines Appendix 3. However, even with a convergence reached, the minimum amount of simulations allowed is still 50.

4.2.2 Evi

Modelling the Geometry

As in Pathfinder, Evi allows for the importing of .dxf files of the GA. However, the allowed file size is considerably smaller, and therefore the GA must be cleaned up from anything unnecessary for the modelling of the specific decks (this means unused layers and features drawn in the GA). This clean-up can take a significant amount of time, but once it is completed the GA can be imported into their respective decks. Also, the topology modelling is quite restricted. Spaces must be modelled in straight lines, and preferably using rectangular shapes connected with a "unite" door. It is possible to use polygonal shapes, but nodes can't be spaced too close together before the model reads an error. In practice, this means the extra fidelity gained from using complex polygonal spaces is not able to be utilised, and as such the spaces must be modelled using combinations of rectangles to approximate the geometry. This approximation can lead to some inaccuracy with regards to how agents interact in spaces with curved walls. Also, some useful CAD tools are either missing (such as a rotate tool) or very lacking in functionality (the array tool will only array a single space directly adjacent to itself, with no option of offsetting).

Otherwise, the topology modelling tool is simple to use and intuitive, and the ability to assign spaces different categories (cabins, corridors, public spaces) helps make large changes very quickly. An example of this is that all fire doors can be selected from a drop-down menu and their widths changed simultaneously. In total, the environment modelling took **15h 30min** to complete.

Modelling the Agents

The IMO agent profiles including crew behaviour are all built into the software. The actual assigning of passenger and crew to spaces is as simple as defining the number of initial passengers and crew in the properties of the space. Then, before running the simulation, the populations are distributed at random at pre-defined probabilities. These prebuilt demographics can of course also be edited if needed, but in the case of fulfilling IMO requirements, this is not necessary. In total, the time taken to assign passengers and crew took **1h 41min.**

Setting up and Running the Simulations

One of the strengths of the Evi software is that it was designed primarily for the use of conducting evacuation analyses for ships. Also, as the software itself is aimed to calculate an evacuability index using the Monte Carlo method [41], it is designed to run simulations in large batches. Therefore, the time taken to run 500 simulations is merely dependent on processing power, and there are no manual intermittent steps necessary.

Evi also supports the use of scripts natively and has a large and extensive library of script commands available to customise the simulation runs. Using these commands allows for every aspect of the simulation to be customised and automated, including the amount of simulations run with the same population, the behaviour profiles assigned and even the objectives of the crew. As such, the time taken to run a full batch of 500 runs took only **2h 40min** to complete.

4.3 User Experience Discussion

As there are not many significant differences in the numerical results (besides the way that reaction times are handled), the user experience and practicality of the software is pushed into the limelight. As mentioned earlier, when viewing the evacuation analysis problem from the designer's perspective, the time taken to perform the task becomes significant (summarised in Table 4).

When it comes to the modelling experience, both pieces of simulation software were quite different. While both programs allowed for the importing of a GA, Pathfinder had a more

Table 4: Times taken to perform various simulation tasks

Task	Pathfinder	Evi
Geometry Modelling	10h 29min	15h 30min
Agent Modelling	2h 59min	1h 41min
Running Simulation x 500	16h 58min	2h 40min
Running Simulation x 1	*2min*	*<1 min*
Total Duration	30h 26min	19h 51min

robust set of design features and was more capable of handling larger CAD drawings. The modelling of the geometry was more time efficient on Pathfinder as duplicating and mirroring features were easier to use and more forgiving than in Evi, and Evi lacked some quality-of-life features such as freely being able copy/paste elements (such as cabins) or to undo actions. Also, Evi required for rather significant cleaning of the GA file, removing all unnecessary detail, before being able to be loaded into the Evi software, partially accounting for the 5 hour difference in time taken for the geometry modelling.

However, when it comes to the distribution of passengers and crew, it becomes clear that Evi was built from the ground up to be used in the evacuation analysis of ships. The ability to classify different topological elements as 'Cabins', 'Public Spaces', 'Corridors' and different types of doors often seen on ships, meant that each element could have custom attributes assigned to them. For example, assigning public space's and cabin's maximum population capacities would then automatically distribute the correct number of agents within, depending on the scenario. On the other hand, with Pathfinder each cabin and public space had to have their populations distributed individually, leading to a very tedious process when setting up e.g. a cabin area. Additionally, attributes such as assigned assembly stations had to be assigned to the agent individually, rather than the cabin and its occupants.

Finally, the largest difference comes in the running of the simulation itself. Evi is designed with running the IMO simulation cases in mind, as it has easy batch-running capabilities allowing for the running of the 500 simulations whilst randomising the demographic distributions in between. This allows for the running of the entire batch of simulations to only take the observed 2h 40min. However, in Pathfinder, randomising the population seeds will have to be done manually in between simulation runs, significantly increasing the time taken to complete the simulations. While scripting capabilities have been added to Pathfinder since these tests were run, there is still the issue of the high-resolution geometry causing the calculation to take a long time.

Overall, modelling the geometry is more time efficient on Pathfinder with the greater number of advanced design tools available, even though the model generated can be more detailed, with higher fidelity. However, when it comes to running a large batch of simulations, Evi is the more efficient choice with the software being purpose built to perform the IMO simulation batches unsupervised, whereas Pathfinder requires significantly larger time spent actively setting up each simulation and running them.

5 Conclusions

In summary, evacuation analysis is a subject of growing importance for those looking to evaluate and improve the safety of a passenger ship's design. However, as this is a difficult topic centred around human psychology, there is no clear consensus on the best method to perform the analysis. One can take a very high-up Macroscopic view of the scenario, analogising people evacuating as a fluid flowing through a system of pipes and tanks; or one can take a very focused Microscopic view, treating each person as an individual agent and simulating their decision making and movements based purely on their own perspective. The optimal choice would lie somewhere in the middle of that spectrum as a Mesoscopic model.

Identifying this need, the IMO has already placed regulations requiring the performing of an evacuation analysis in the passenger ship design phase to evaluate the safety of the general layout, and giving guidelines for two methods: a (Macroscopic) simplified method, and a (Microscopic) advanced method. While the guidelines for the simplified method goes into great detail as to how to perform the calculations and evaluate the results; the advanced method is vaguer, providing population demographics and their attributes, but not prescribing any one manner of performing the analysis. This gives a certain freedom in how to model the environment and the agents, with a set of validation tests to evaluate the modelling method.

As such, there are many different types of software on the market that can perform advanced evacuation analyses using different modelling methods, and this study evaluated two of them: Evi and Pathfinder. The evaluation was based on: how the numerical simulation results compared, the time taken to setup the analysis, the time taken to process the calculation and the user experience for the designer. Furthermore, this was compared to running the simulation using a simplified analysis.

In the end, the numerical results obtained from the two software was very similar, both in the magnitude and the shape of the completion time curve produced, differing only 9% in the maximum completion time. However, despite its lack of resolution, the simplified method reached a completion time right in the middle of the Pathfinder and Evi simulations, differing by 4% and 5% respectively, showing that while lacking detail and making large assumptions it does still hold some validity.

The most notable differences came in the user experience. While both software suites were similar in how to approach building the simulation environment, Pathfinder had more feature rich design tools, a more modern user interface and allowed for higher resolution geometries, all resulting in a faster time to model the geometry. However, key benefits for Evi came from the fact that it was designed specifically for the evacuation analysis of ships, and as such had the IMO requirements built in. This meant that assigning assembly stations and distributing agents was made simple, as each room could have their starting populations defined, rather than placing agents individually and modifying their features. Most critically this included the ability to run the simulation in batches. These are important factors to consider as a designer when choosing what tool to use for an evacuation analysis.

In the end, while both Evi and Pathfinder have some fundamental differences in their approach to evacuation analysis, they are both excellent tools and an important part of furthering the knowledge and technology in the field. While regulations do not require them, both software packages continue to push the envelope with how to improve their simulations taking into account features such as elevators/escalators or ship motion and LSA embarkation. As such, they are clearly looking towards a future with ever safer passenger ships.

While the current requirements for simplified analysis have been shown to have validity, as the ship geometries grow in size and complexity, it becomes increasingly difficult to design, validate and interpret the results from a spreadsheet tool. Therefore, from a user experience and time management viewpoint, it becomes more economical, efficient and reliable to use a purpose-built design tool such as Evi or Pathfinder.

Future studies should aim to further validate the theory behind evacuation analysis, with a particular focus on studying effects of the evacuation process unique to passenger ships such as heeling. One of the large disadvantages of evacuation analysis methods is the low amount of real-world verification, which is why publicly published projects such as SAFEGUARD are so important.

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Appendices

A1 Tables from Simplified Analysis Guidelines

Table A1.1: Values of initial specific flow and initial speed as a function of density [16]

Type of facility	Initial density D (p/m^2)	Initial Specific flow Fs (p/m/s)	Initial speed of persons S (m/s)
Corridors	0	0	1.2
	0.5	0.65	1.2
	1.9	1.3	0.67
	3.2	0.65	0.20
	≥ 3.5	0.32	0.10

Table A1.2: Values of maximum specific flow [16]

Type of facility	Maximum specific flow Fs (p/m/s)
Stairs (down)	1.1
Stairs (up)	0.88
Corridors	1.3
Doorways	1.3

Table A1.3: Values of specific flow and speed [16]

Type of facility	Specific flow Fs (p/m/s)	Speed of persons (m/s)
Stairs (down)	0	1.0
	0.54	1.0
	1.1	0.55
Stairs (up)	0	0.8
	0.43	0.8
	0.88	0.44
Corridors	0	1.2
	0.65	1.2
	1.3	0.67

A2 Tables from Advanced Analysis Guidelines

Table A2.1: Population composition (age and gender) [16]

Population groups - Passengers	Percentage of passengers (%)
Females <30 years old	7
Females 30-50 years old	7
Females >50 years old	16
Females >50 years old, mobility impaired (1)	10
Females >50 years old, mobility impaired (2)	10
Males <30 years old	7
Males 30-50 years old	7
Males >50 years old	16
Males >50 years old, mobility impaired (1)	10
Males >50 years old, mobility impaired (2)	10
Population groups - Crew	**Percentage of crew (%)**
Female crew	50
Male crew	50

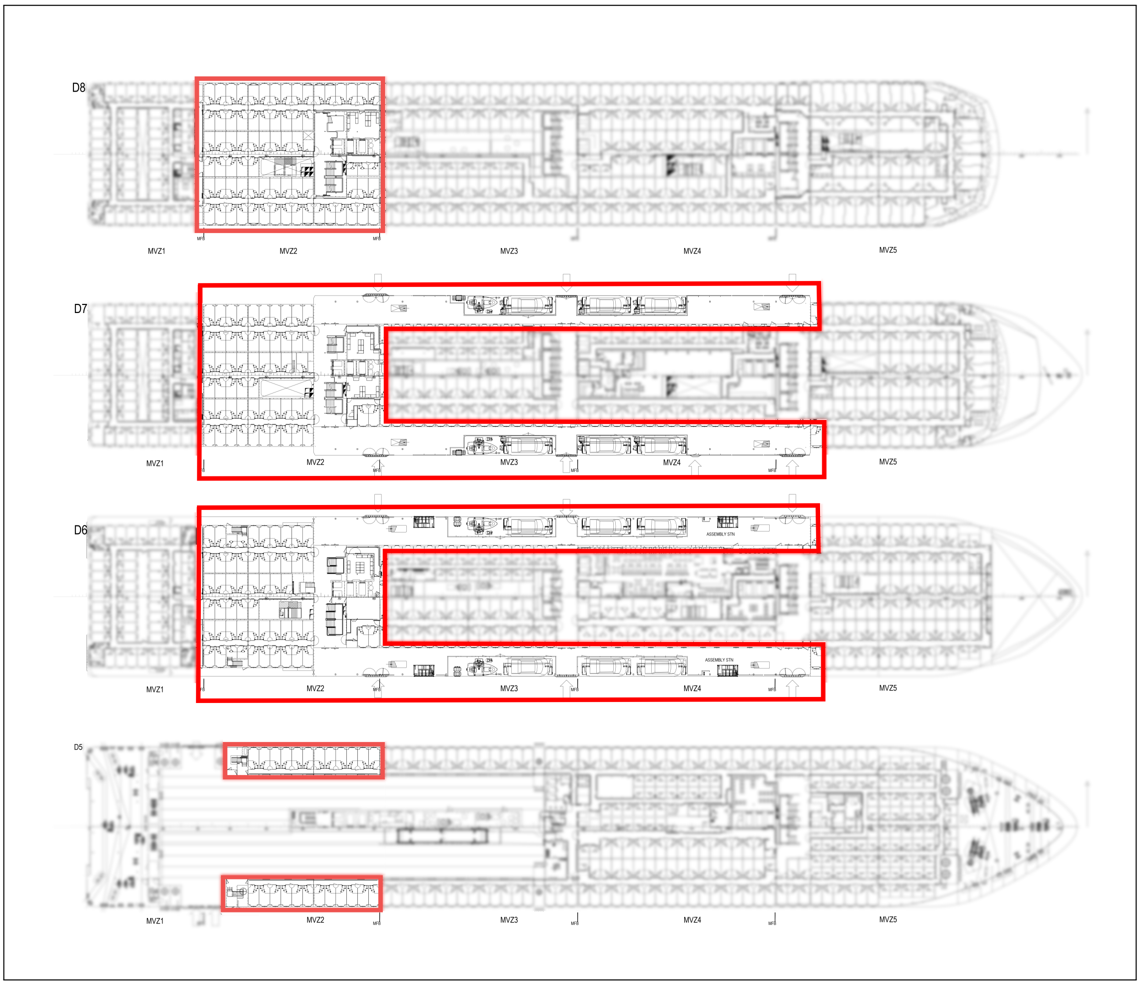
Table A2.2: Uniform distribution for walking speeds on flat terrain (e.g. corridors) [16]

Population groups - Passengers	Walking speed on flat terrain (m/s)	
	Min	Max
Females <30 years old	0.93	1.55
Females 30-50 years old	0.71	1.19
Females >50 years old	0.56	0.94
Females >50 years old, mobility impaired (1)	0.43	0.71
Females >50 years old, mobility impaired (2)	0.37	0.61
Males <30 years old	1.11	1.85
Males 30-50 years old	0.97	1.62
Males >50 years old	0.84	1.4
Males >50 years old, mobility impaired (1)	0.64	1.06
Males >50 years old, mobility impaired (2)	0.55	0.91
Population groups - Crew	**Walking speed on flat terrain (m/s)**	
	Min	Max
Female crew	0.93	1.55
Male crew	1.11	1.85

Table A2.3: Uniform distribution of walking speeds on stairs [16]

Population groups - Passengers	Walking speed on stairs (m/s)			
	Stairs down		Stairs up	
	Min	Max	Min	Max
Females <30 years old	0.56	0.94	0.47	0.79
Females 30-50 years old	0.49	0.81	0.44	0.74
Females >50 years old	0.45	0.75	0.37	0.61
Females >50 years old, mobility impaired (1)	0.34	0.56	0.28	0.46
Females >50 years old, mobility impaired (2)	0.29	0.49	0.23	0.39
Males <30 years old	0.76	1.26	0.5	0.84
Males 30-50 years old	0.64	1.07	0.47	0.79
Males >50 years old	0.5	0.84	0.38	0.64
Males >50 years old, mobility impaired (1)	0.38	0.64	0.29	0.49
Males >50 years old, 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
Female crew	0.56	0.94	0.47	0.79
Male crew	0.76	1.26	0.5	0.84

A3 General Arrangement of Simulated Ship



A4 Results of the Evi Simulation Batch

MVZ2

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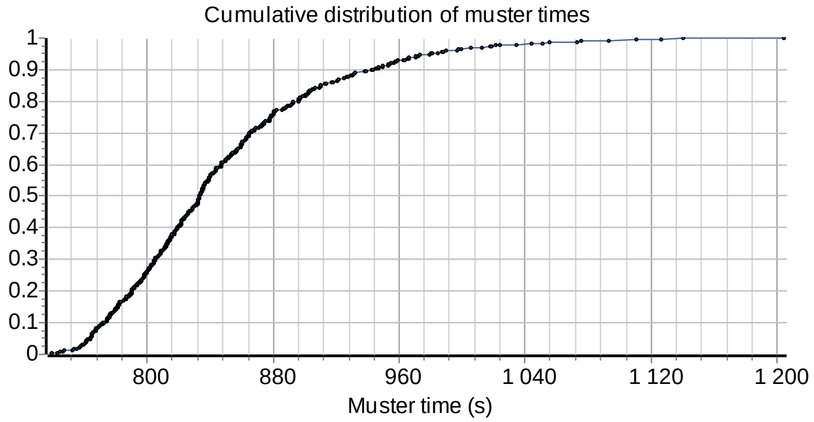

Crew	0
Pax	814
Total	814

Runs (N)	500
Muster time (1.25 × 95%ile (R + T))	20m 26s
Performance standard*	40m 26s
Mean agent travel time	1m 30s
Mean agent travel distance	30.45m

Muster time (s)	**Max**	**95 %ile**	**Mean**	**Min**
Overall	1204.50	980.75	847.09	738.50
Ass. A	1073.50	828.50	740.94	618.50
Ass. B	1110.50	880.00	764.51	659.50
Ass. C	1051.00	905.00	799.48	709.50
Ass. D	1204.50	942.25	801.19	702.50

Zone	**0**	**2**	**Totals**
Runs	0	500	
Ass. A	0	33	33
Ass. B	0	90	90
Ass. C	0	173	173
Ass. D	0	204	204

* Based on the assumption that embarkation and launch take 30 minutes

Page 1 of 2

MVZ2

Evi v4.2.0 08.08.2019 01:30

Run	Muster time	Last agent start location	Zone	Muster station	Congestion
323	20m 5s	d6-Cabin41	2	Ass. D	No
238	19m 1s	d6-Cabin47	2	Ass. D	No
448	18m 47s	d6-Cabin46	2	Ass. D	No
481	18m 31s	d6-Cabin113	2	Ass. B	No
393	18m 14s	d6-Cabin44	2	Ass. D	No
140	17m 56s	d6-Cabin48	2	Ass. B	No
423	17m 54s	d6-Cabin44	2	Ass. A	No
118	17m 36s	d6-Cabin45	2	Ass. D	No
427	17m 31s	d6-Cabin41	2	Ass. C	No
133	17m 24s	d6-Cabin42	2	Ass. C	No
45	17m 15s	d6-Cabin114	2	Ass. D	No
357	17m 4s	d6-Cabin48	2	Ass. D	No
191	17m 1s	d6-Cabin45	2	Ass. D	No
313	16m 59s	d6-Cabin45	2	Ass. C	No
430	16m 58s	d6-Cabin47	2	Ass. D	No
308	16m 53s	d6-Cabin41	2	Ass. D	No
57	16m 46s	d6-Cabin43	2	Ass. D	No
370	16m 40s	d6-Cabin48	2	Ass. D	No
76	16m 38s	d6-Cabin43	2	Ass. B	No
285	16m 37s	d6-Cabin45	2	Ass. B	No
131	16m 30s	d6-Cabin43	2	Ass. B	No
311	16m 29s	d6-Cabin44	2	Ass. D	No
38	16m 27s	d6-Cabin48	2	Ass. D	No
155	16m 25s	d6-Cabin43	2	Ass. C	No
128	16m 21s	d6-Cabin43	2	Ass. A	No
399	16m 21s	d6-Cabin47	2	Ass. B	No
145	16m 19s	d6-Cabin114	2	Ass. C	No
43	16m 14s	d6-Cabin48	2	Ass. D	No
105	16m 12s	d6-Cabin48	2	Ass. D	No
435	16m 11s	d6-Cabin46	2	Ass. D	No
195	16m 11s	d6-Cabin42	2	Ass. C	No
159	16m 7s	d6-Cabin114	2	Ass. D	No
445	16m 7s	d6-Cabin43	2	Ass. D	No
73	16m 5s	d6-Cabin45	2	Ass. B	No
119	16m 4s	d6-Cabin114	2	Ass. C	No
143	16m 3s	d6-Cabin113	2	Ass. A	No
404	15m 60s	d6-Cabin43	2	Ass. C	No
190	15m 59s	d6-Cabin47	2	Ass. D	No
417	15m 58s	d6-Cabin113	2	Ass. D	No
69	15m 57s	d6-Cabin46	2	Ass. C	No
322	15m 55s	d6-Cabin43	2	Ass. D	No
385	15m 54s	d6-Cabin48	2	Ass. C	No
250	15m 54s	d6-Cabin42	2	Ass. C	No
81	15m 53s	d6-Cabin43	2	Ass. B	No
89	15m 50s	d6-Cabin43	2	Ass. C	No
6	15m 50s	d6-Cabin47	2	Ass. A	No
171	15m 47s	d6-Cabin48	2	Ass. D	No
122	15m 47s	d6-Cabin42	2	Ass. D	No
178	15m 47s	d6-Cabin48	2	Ass. C	No
175	15m 46s	d6-Cabin44	2	Ass. B	No
425	15m 44s	d6-Cabin114	2	Ass. A	No
153	15m 43s	d6-Cabin43	2	Ass. D	No
297	15m 39s	d6-Cabin41	2	Ass. B	No
192	15m 38s	d6-Cabin43	2	Ass. A	No
314	15m 33s	d6-Cabin44	2	Ass. D	No