AALBORG UNIVERSITY

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Fundamentals of Egress Simulation: A Practical Exploration Through Thunderhead Engineering Pathfinder

M. Sc. in Risk & Safety Management

Fourth Semester – Thesis Report

Author: Shaminda Pushpa Kumara Panditha

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Abbreviations

ARTICLE – refers to the article given in the DOI: https://doi.org/10.3390/app12094213 (Zhang, et al., 2022)

GUI – Graphical User Interface

IMO – International Maritime Organization

ISO – International Organization for Standardization

NIH – National Institute of Health

NLM – National Library of Medicine

PBL – Problem Based Learning

PF – Pathfinder

USA – United States of America

Chapter 1: Introduction

Global warming and climate changes have brought many adverse effects and disasters recently in addition to jeopardizations that take place due to the direct human interventions. Modern technology development has facilitated more complex structures and buildings that inhouse dense people interactions on those facilities. Emergency response on such occasion demands a need to predict human evacuation behaviour studies under more realistic conditions to minimize the casualties and fatalities. Evacuation analyses are increasingly becoming a part of performance-based analysis to life safety levels of buildings moving from manual hand calculations with SFPE principles more and more towards the egress modelling (Kuligowski, Erica D.; Peacock, Richard D., 2005). Therefore, egress simulation as a vital and supportive tool for egress analysis is becoming more and more important with the dynamically changing world today.

The Grenfell Tower fire in London resulted the lost of 72 lives in 2017 highlighting the complexities of evacuation from high-rise buildings and teaching the lessons of importance of specialized training for firefighters to handle such complex emergencies (Stokel-Walker, 2017). One of the main facilitations of egress simulation is to be used in evacuation analyses, which is a main motivator for the growing considerations on Egress Simulations.

Due to many passenger-ship loss of life accidents worldwide, Internationals Maritime Organization (IMO) has developed guidelines since May 1999 for the egress analysis of ro-ro passenger ships (Kim, H; Park, J. H.; Lee, D; Yang, Y. S., 2004). In addition, IMO has also given a special consideration on Egress Simulation Tools and has specified guidance on validation and verification of evacuation simulation tools (such as Pathfinder) under four different categories (component testing, functional verification, qualitative verification and quantitative verification) which includes all inclusive 13 test specifications under Appendix 2 (IMO, 2016, p. 9).

Researcher has also simulated these tests scenarios in Pathfinder and made some attempts to compare by benchmarking with similar test scenarios conducted through another egress simulation tool, namely the AnyLogic which has been presented in the ARTICLE (Zhang, et al., 2022).

Researcher's familiarity on Pathfinder due to hands on experience through this MSc study was an additional motivator to explore in detail on Pathfinder in addition to Pathfinder's many advantages and capabilities which are further discussed under the section "2.5.5 What is the purpose of Egress Simulation".

All these motivating factors catalysed the appetite of researcher to dig in detail on the *Fundamentals of Egress Simulation with a practical exploration through Pathfinder* including an initial question like *"How can agent-based egress simulation fundamentals, using the Thunderhead Engineering Pathfinder, be applied to model, evaluate and verify the performance of Egress Simulation?".*

To explain briefly about the following chapters, chapter two discusses on literature review and chapter 3 discusses on methodology. The chapter 4 discusses on the role of egress in the risk and safety context. Chapter 5 presents the problem formulation of the research and chapter 6 is reserved for the delimitation. The fundamentals of egress simulation, exploration with pathfinder is discusses in chapter 7 while chapter 8 reserved for the discussion, chapter 9 for conclusion and references are presented in chapter 10.

Chapter 2: Literature Review

2.1 Hazard

Any source that has a potential to cause adverse effects or harm is a Hazard. It may be physical, chemical, biological or even organizational or any other that has the potential of causing adverse effect (illness, damage, injury or even the loss).

2.2 Risk

The risk is defined using following equation shown below.

Risk (R) = Probability (P) x Consequence (C)

Consider an activity having an event with the probability of occurrence (P) and the consequence (C), then the product between these 2 is the Risk (R).

(Faber, Statistics and Probability Theory, 2012)

2.3 Danger

Following definition is stated in an article that discusses on the connection between safety engineering of healthcare and civil law.

“Danger is defined as the unreasonable and unacceptable combination of hazardous risks. As noted above, any risk of serious injury or death is unreasonable and unacceptable if reasonable accident prevention methods could eliminate it.” (Reihart, 2014)

In addition to above Danger implies a time concern calling for a necessity of an immediate attention.

2.4 Emergency Management Cycle

The emergency management cycle consists of 4 main stages as follows

- Mitigation: Once identified an emergency, all attempts such as planning to avoid the next occurrence emergency. If any means of preventing the emergency is found, it should be prioritized.
- Preparedness: The process of getting ready to face the occurrence of next emergency.
- Response: All responsive activities such as fire fighting, egress
- Recovery: Implementing the systems back in operation

This process can be performed continually cyclic until the emergency is prevented.

2.5 State of the Art – Egress

The simple meaning of Egress as a verb is the action of leaving a place og going away out of a place. In other words, as it usually discusses in Risk and Safety contexts is the "Evacuation".

2.5.1 What is Egress Analysis

Analysis is the detailed study on the given context when the topic is usually an important one which is very much relevant for Egress Analysis as a context that usually associate with emergencies of dangers and consequences could become life threating. So, all types of studies including the simulation studies regarding the evacuation could be considered under Egress Analysis.

2.5.2 What is Egress Simulation

In an article from National Library of Medicine (NLM) [of National Institute of Health (NIH) of USA] that discuses on how simulation can be used to improve healthcare management and policy, states following definition on simulation.

"Simulation is a technique that evokes or replicates substantial aspects of the real world, in order to experiment with a simplified imitation of an operations system, for the purpose of better understanding and/or improving that system." (Lamé & Simmons, 2020)

Following explanation presents a good explanation on Egress Simulation and its basic usage.

"A method to determine evacuation times for areas, buildings, or other spaces. It is based on the simulation of crowd dynamics and pedestrian motion. Egress simulations are used in fire safety engineering analyses." (Cereda, Ferracuti, Gasparetto, Sciarretta, & Zanella, 2021).

Below explanation is found in Computational Evacuation Modelling in Wildfires by Enrico Ronchi & Steven Gwynne.

"An evacuation model is a qualitative or quantitative conceptual framework used to depict evacuee response, assist decision-making, and finally improve people safety. Computational evacuation modelling refers to the implementation of this conceptual framework into a computer, typically to quantify evacuee performance." (Enrico Ronchi, Steven Gwynne, 2019)

International Maritime Organization (IMO) expects Egress Simulation to model each person's behaviour in an emergency in relation with the on-board environment to evaluate the evacuation performance. It states as follows.

"Advanced evacuation analysis is taken to mean a computer-based simulation that represents each occupant as an individual that has a detailed representation of the layout of a ship and represents the interaction between the occupants and the layout." (IMO, 2016)

2.5.3 What is Agent-Based Simulation

AnyLogic is another Agent-Based Egress Simulation software like Pathfinder. Their website states following explanation on Agent-Based Simulation Modelling.

"Agent-based modeling focuses on the individual active components of a system. With agent-based modeling, active entities, known as agents, must be identified and their behavior defined. They may be people, households, vehicles, equipment, products, or companies, whatever is relevant to the system. Connections between them are established, environmental variables set, and simulations run." (AnyLogic, 2021)

2.5.4 The Approach and Type of Egress Model

Thunderhead Engineering Pathfinder takes an approach that focuses and facilitates the egress modelling and simulation based on individual's characteristics and behaviours. Therefore, it is called an **Agent-Based Egress modelling and simulation approach**.

In this approach due to its attempt to address in detail aspects, Pathfinder is also categorized under the type of **Microscopic Simulation Model**.

2.5.5 Relevant Standards

There are bunch of standards and guidelines relevant for Egress. Other than IMO, mainly ISO standards serve on achieving better egress from entities. Below is an example selected randomly within many others. The ISO 21542:2021 "Building construction – Accessibility and usability of the build environment" attempts to ensure built environment is safe for everyone.

"Accessibility standards ensure that the built environment is inclusive, safe, and usable for everyone, regardless of their abilities." (ISO, 2020)

2.5.6 The Purpose and Objectives of Egress Simulation

The ultimate idea or in otherwards the whole purpose of Egress Simulation is to bring people quickly in safety, in a case of an emergency. To serve and achieve this purpose Egress Simulation has been improved today to some extent that it can now achieve many objectives, not only just finding the total evacuation time. Some of those basic objectives – evident after working with Pathfinder – are discussed below.

- **Safe Evacuation Time**

The Egress Simulation must estimate the time taken for occupants to evacuate the emergency area and arriving at the safe area. It should be verified to be lesser than an accepted time limit implying that occupants reached safety zone before the danger criteria triggers (ASET > RSET). In an emergency such as a building fire or a sinking passenger ship, occupants must be evacuated quicker as possible before occurring the danger conditions.

- **Identification of bottlenecks and hazardous points**

By studying Egress Simulation experts can identify bottlenecks and hazardous positions in evacuation paths. Then they can take necessary remedies to avoid the bottlenecks and hazardous conditions before occurring the emergency. An example would be a narrow staircase of a passenger ship between deck levels. Providing alternative paths or widening the staircase would be possible solution to such problem.

- **Human behaviour analysis**

Egress Simulation models can be studied to understand human behaviour in emergencies. These models can be incorporated with human behavioural factors such as decision delays, individual and grouping effects, walking speeds at different terrains and hazardous conditions. Early understanding of such behavioural aspects makes provisions for the possible improvements for the identified positions.

- **Cheaper and Low Risk Solution**

Presently with the development of computer and its related technology (software like PF etc.), Egress Simulation has become a relatively cheaper solution than actual experiments. Saving of resources including the time savings is a benefit in addition to the minimal risk that can be associated in actual evacuation drills and experiments that might can also be driven into some hazardous situations. The convenience in repeatability, changeability and thereby the ability of performing sensitivity testing etc. are further advantages but can also be considered under the financial advantages.

- **Facilitation of Risk involved Decision Making**

As it is discussed above, early identification of bottlenecks, human behaviours and other important aspects provide the possibility of seeking Risk informed solutions that minimized the future potential damage due to an emergency.

Following are few examples that Egress Simulations, by fulfilling above objectives, play a vital role and are widely used in

- Safety Planning and Emergency Preparedness
- Regulatory compliance and Standards
- Improving designs and Emergency Response Protocols

2.6 Timeline approach of Egress

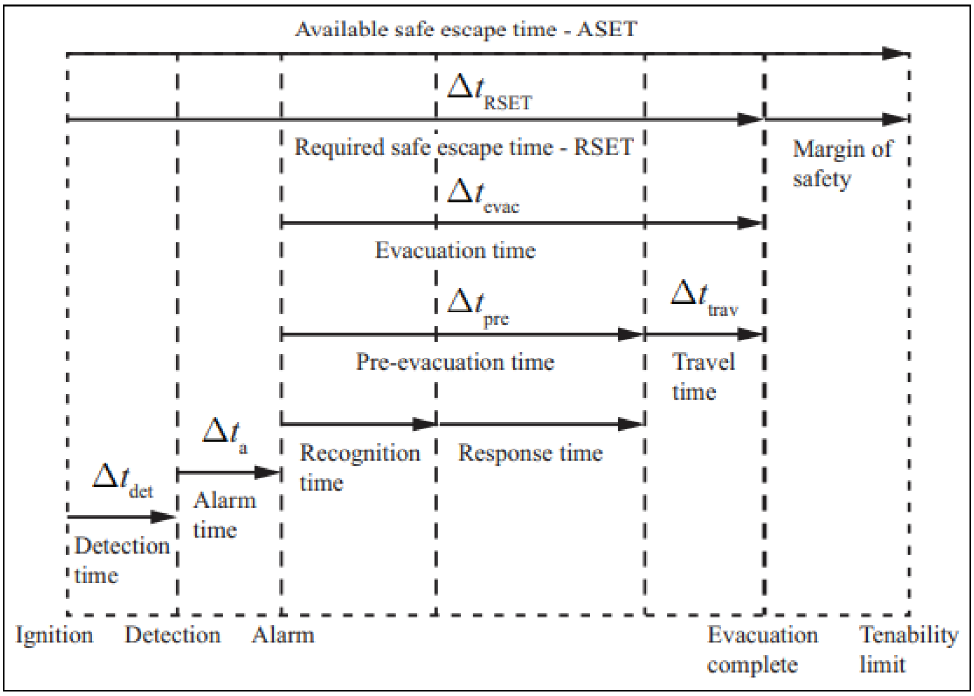


Figure 2. 1: Components of Egress Timeline ((Xie, Chen, Kwan, & Yao, 2021)

The following is a brief explanation of the terms used in above figure. A case of a fire can be used as an example for the clarity.

- Point of Ignition: The point of time that emergency occurs. (Fire started)
- Δt_{det}: It can take some time to observe or sense the emergency. (A smoke detector or somebody sees the fire)
- Δt_{a}: The time between detecting and alarming. (Time taken to start the fire alarm since fire detection)
- Recognition Time: Since occupants hear the alarm, the time taken to recognise that its an emergency to evacuate.
- Response Time: The time taken to start responding after the recognition of the emergency.
- Δt_{pre} (Pre-Evacuation Time): The total time taken to start evacuation movement after recognition of the emergency alarm. (the summation of the recognition and the response times)
- Δt_{trav} (Travel Time): The time taken to reach to the safe location after starting the evacuation movement.
- Δt_{evac} (Evacuation time): The time after the recognition of the emergency until reaching the safe location. (= Δt_{pre} + Δt_{trav})
- Δt_{RSET} (RSET or Required Safe Escape Time): The time after occurrence of the emergency until occupants reach the safe location.
- ASET (Available Safe Evacuation Time): The time after occurrence of the emergency until the occurrence of the danger condition. (An example danger condition would be the collapsing of the building due to the fire)
- Margin of Safety: To be safe ASET > RSET.

Chapter 3: Methodology

This thesis research was conducted as the fourth and final semester research project of M. Sc. Education, Risk & Safety Management of University of Aalborg, Esbjerg. The base of knowledge refers not only to research activities conducted based on this research project but also the knowledge gathering through out the previous semesters with those activities such as classroom and online lectures, seminars, semester group projects combined with Problem Based Learning (PBL) of AAU, guided industry visits and guided knowledge gathering on internet.

This research project was a self-study project with the guidance wherever necessary by the project supervisors as per the accepted semester structure of the education. This research study combines qualitative and quantitative data collection and also analysis and thereby can be considered as research of Mixed Method.

The knowledge building was mainly based on online academic publications and standards. The International Maritime Organization (IMO) guidance and standards, the Society of Fire Protection Engineers (SFPE) publications and Thunderhead Engineering Pathfinder user manual were frequent references in the research study as well as in the report – with due citations where necessary – since beginning and throughout, as initial project approach had a focus on Maritime related Egress Simulation.

This research study focuses on Fundamentals of Egress Simulation while researching the same through Pathfinder Egress Simulator. In addition, some of IMO recommended tests – for Egress Simulator tools – were modelled and simulated on Pathfinder and tried to be verified and validated while benchmarking through the results found on same tests presented on the ARTICLE (Zhang, et al., 2022). In the validation test (test 11), another test used for benchmarking from (Lei, et al., 2012), other than the one from ARTICLE.

Already at present, it can be seen the association of Artificial Intelligence (AI) in almost everywhere. This research also used AI as a supportive tool, mainly ChatGPT (GPT-4), for searching relevant literature on internet and once a while for the idea inspiration. All AI referred content has been personally reviewed and cited wherever used and the verbatim in this report is generated by the researcher.

Since this is mainly an individual research effort, critical insights of subject experts were an advantage which was served and fulfilled by the AAU project supervisors. The process includes some physical meeting sessions and brainstorming with subject experts.

Behaviours and Behaviors: Both terms were used appropriately in this thesis report to express the same meaning “the way in which someone acts”. But the word “Behaviors” is used specifically at the locations where it has some relevance with Pathfinder and also to keep the same Pathfinder user interface caption “Behaviors”.

Chapter 4: Egress in Risk & Safety Context

Usually the terms Hazard, Risk, Danger, Emergency and Egress or Evacuation finds in the same articles frequently. This is because of their connection in the real-world practice. Since hazard is having a potential of coursing harm, risk is measured to quantify to see whether any danger is available. If danger presences, then it becomes an emergency and might need for the evacuation.

A fire is a common hazard that occurs frequently (availability of probability or likelihood) causing adverse effects (consequences) which is a common risk aspect that has records of happened in the history for example within buildings or maybe in a cruise ship. So, once fire occurred, buildings collapse and cruise ships sink putting people in danger and calling for emergency response and probably the evacuation needs. The evacuation becomes a rescue method which might need huge efforts that involves usually saving lives as well. This is the context where the emergency management comes into play an important role.

As emergency management process is considered in four main stages, mitigation (once emergency is identified), preparedness for the identified emergency (that can occur again), response (if it occurred) recovery (restoring the systems back in operation) and works in cyclic form again in the next cycle starting from mitigation the next emergency. Egress has a main role in emergency management cycle which actively performs in mitigation and preparedness stages with egress planning, egress simulation studies etc. and in the response stage it gets into use in actual practice.

4.1 Pathfinder's positioning in Timeline Approach of Egress

Refer figure 2.1: Components of Egress Timeline

It is very vital to have a higher safety margin for the successful emergency and rescue operations. That means theoretically the ASET must be bigger and RSET must be smaller. Since emergency and danger conditions can become less controllable once the emergency has occurred, the controllability of ASET is less practicable. Then it is RSET that can be attempted to minimize to get a higher safety margin.

With reference to timeline, RSET can be minimized by minimizing the evacuation time and in otherwards by minimizing its 3 subcomponents, the recognition, response and the travel time. The timeline's relationship to Pathfinder finds here that Pathfinder as an agent-based Egress Simulator, its focus is mostly kept on simulating the egress movement or the traveling part that means on the travel time which corresponds to timeline of egress. Presently, Pathfinder does not differentiate recognition and response times but to represent both, Pathfinder has a parameter called "initial delay" that finds when modelling Pathfinder occupants.

Chapter 5: Problem Formulation

How can the fundamentals of Egress Simulation be explored through Pathfinder-based experimentation?

- What are the theories and how can these theories be applied on Egress Simulation?
- How can Pathfinder be used in simulating the tests recommended by IMO for Egress Simulation tools?
    - How can real world entities such as buildings and humans be represented and modelled using Pathfinder?
    - How can different human characteristics and behaviours be incorporated in simulation models in Pathfinder?
    - How can Pathfinder's Simulation performance be evaluated, verified and validated?
    - What are the limitations, advantages and disadvantages of using Pathfinder for Egress Simulation?

Chapter 6: Delimitation

This research is mainly an individual attempt to discuss on Egress Simulation where the availability of resources was very limited that could be contributed to serve the purpose.

Research was mainly qualitative apart from some Pathfinder testing which presented some quantitative input for test verification and validation in the research. Inclusion of surveys and interviews could have added value, but resource limitation avoided the possibility.

Chapter 7: Fundamentals of Egress Simulation Exploring with Pathfinder

Under this chapter the Fundamentals of Egress Simulation will be discussed while exploring the same in Thunderhead Engineering Pathfinder.

Since this exploration refers to Thunderhead Engineering Pathfinder, following content is merely developed by the researcher's practical research experience of the same software and combining with the information extracted from Pathfinder User Manual 2024.2 (Thunderhead Engineering, 2024). *The purpose of this notification is to minimize many frequent citations that would otherwise be applied in the middle of the following content and then would interrupt the readability.*

Pathfinder as an agent-based Egress Simulator has assigned a prominent consideration on its occupants (or agents representing usually the humans), occupant behaviours and occupant movement space (buildings, walkways etc.). All these are to be modelled in the modelling Graphical User Interface (GUI) and the simulation is to be shown in a separate GUI. It uses another GUI to show results such as graphs etc.

The Pathfinder simulation for the IMO test no 1 can be considered as an example on presenting the Simulation run GUI. Further, these figures 7.1 to 7.4 verifies visually that PF maintains the set walking speed in a corridor.

Test 1: Maintaining set walking speed in a corridor

Figure 7. 1: Occupant is at its initial position. (time is 0 s)

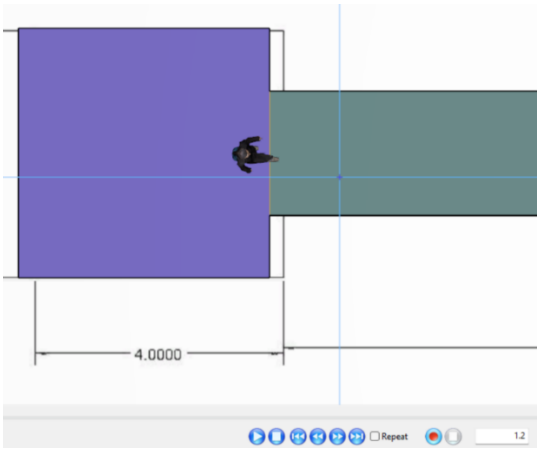


Figure 7. 2: Occupant enters the room 1 (Time is 1.2 s, zoom in view)

Figure 7. 3: Occupant is walking in the middle of the room 1

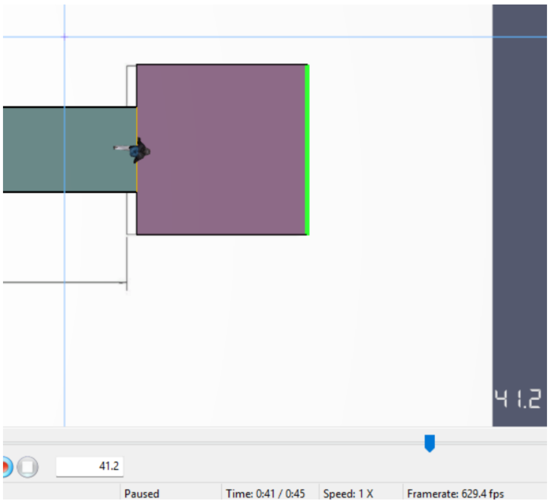


Figure 7. 4: Occupant is leaving the room 1 (Time is 41.2, zoom in view)

3D Graphical views confirm that occupant has taken 40 s (= 41.2 – 1.2 s) to walk through the corridor. This walking time is appreciated as when occupant has the set walking speed of 1 m/s, it should take 40 s to walk through a 40 m long corridor. So, it verifies that occupant maintains the set walking speed in a corridor.

7.1 Occupant Movement Space

In the modelling Graphical User Interface (GUI), Pathfinder facilitates development of floor based geometrical structure, which is the occupant movement space. Manual modelling tools are provided to develop necessary objects in this space such as thin and thick walls, Add Room, Create Ramp or Stair, and Add Door and obstacles.

Either a building floor level, a deck of a ship or an offshore platform, the modelling process is similar that user must model rooms, doors and at least one exit or refuge area for the evacuation purpose of the occupants. Occupants are to be modelled in these room spaces located on the floor levels. The floor levels are to be connected with Staircases, Ramps, Escalators and Elevators with each other.

So, these rooms, staircases, ramps, escalators, elevators and corridors that might be bounded by room walls together with obstacles define the walkways for the occupants which becomes the evacuation pathways in the simulation run. PF evaluates on the fastest egress to occupant including the occupant density in the vicinity and make dynamic speed and route changes in the simulation run.

Pathfinder develops a 3D triangulated mesh in each floor of the movement environment (walkable space) for the occupants' movement in the simulation run and uses a technique called inverse steering. Triggers are used in Pathfinder to influence the performance of occupants in the simulation. In PF triggers are commonly used as signs (Ex: Toilet) and evacuation alarms and once triggers are activated, those occupants influenced change their behaviour, performing the new task which is assigned to them to be performed after the trigger activation.

In addition to simple manual modelling with or without using a sketch as a background supportive image in the modelling GUI, Pathfinder facilitates importing geometry from several CAD formats to develop the simulation environment. Though it has many advantages like saving time and other resources, it has also some of its limitations that are also described in the Pathfinder User Manual 2024.2.

7.2 Occupants

Pathfinder is an agent-based egress simulator that has provided the agent or the occupant motion in two separate modes called Steering mode and SFPE mode. In the steering mode it uses a steering system to move and interact with other occupants and emulate a human behaviour and movement as much as possible. In the SFPE mode it uses a set of assumptions and hand calculations as defined in the *Engineering Guide to Human behavior in Fire* (SFPE, 2019) and occupants do not try to avoid others and even can sometimes penetrate between each other. Further in this mode, the flow is limited by the door widths and velocity is controlled by the occupant density.

User must introduce occupants in the Pathfinder modelling graphical user interface (GUI) and those occupants' performances can be observed in the results GUI. There is a variety of occupant display modes available in PF which are as disks, cylinders, spheres, generic and people, that provides user the convenience of selecting separately in both modelling and results GUIs as appropriate for the presentation and the analysis. In the people display mode it can also be converted into 3D avatars which looks more like people on move specially in the results interface.

The occupant's characteristics are defined in occupant profiles and the actions and activities to be performed are defined in Behaviors. So, in the simulation run, occupants' performance and results are output of the tasks assigned to them in behavior section simultaneously combining with the assigned characteristics in the profile section.

7.2.1 Occupant Profiles

The profile defines the characteristics of occupants such as the colour, avatar, maximum speed and size (radius) and many more, already available with a set of default values. The user must accept the default or indicate appropriate occupant characteristics for every occupant in the profile dialog box either separately or as a group so as required for the simulation.

Since there are many occupant profile characteristics, few of important characteristics are shown below as examples. There are some more selected and interesting characteristics that are in Appendix A for further reference.

- **Occupant Speed:** This is the speed that occupant evacuate in the simulation run. In most cases, user only has to define the maximum speed of the occupant and occupant's actual speed depends on this speed and the terrain being traversed and the density of occupants in the vicinity. Depending on the terrain being traversed (ramp or stair etc.) the assumptions from the Engineering Guide to Human Behavior in Fire (SFPE 2019), comes into play. Otherwise, flexibility is also given that user can model characteristics as of their choice to perform separately in these 3 terrain types.

- **Priority Levels:** A setting that allows the lower prioritized occupants give way to higher prioritized occupants, useful in a crowded situation. As an example, this feature can be used to replicate some medical staffs or police personnel where they usually get prioritized roles in emergencies.

Since occupant speed is an important and fundamental aspect in evacuation (thereby Egress Simulation), further speed specification possibility is available through some of stochastic parameters in PF such as the speed specification using probability distributions. **There are three probability distributions available at present namely, Normal, Uniform and Lognormal**.

Though occupants are depicting the real people in the simulation, some of important demographic factors such as **age and gender** are not directly indicated in the profile characteristics dialog box. But the user is given the possibility of specifying the maximum speed of occupant which is directly relevant for evacuation and correspondent to the effects of age and gender factors. So, some of the age and gender aspects are assumed to be compensated likewise through other available characteristics parameters in Pathfinder.

7.3 Behaviors

The behavior defines the sequence of actions that occupant will take throughout the simulation such as moving to a room, waiting for assistance and go to an exit. This can be considered as the tasks assigned for every occupant that has to be accomplished in the simulation. A sequence of these actions can be assigned one after the other to occupant as required by the user.

Following shows few such example behaviors and some more examples can be found in Appendix B (also that assisted with random Distributions) for further reference.

- **Goto Any Exit:** Occupant takes the fastest route to exit by any available exit. In Pathfinder once exited it is the end of the simulation for the corresponding occupant(s). In otherwards, beyond exit, it represents the safe locations in real context.

- **Initial Delay:** This defines the delay time that occupant waits at its starts position before performing to the next action. This time can be assigned as a constant or using the same above mentioned three distributions, Normal, Uniform or Lognormal. This is one of the frequently used parameters that represents both recognition and reaction time delays in the real context.

- **Goto Elevators:** Asking the occupant to use the elevator. This is another frequently used parameter in the simulations of Highrise buildings with elevators.

7.4 Egress Performance Indicators

As an Egress Simulator Pathfinder presents many Egress Performance Indicators in both qualitative and quantitative forms. Some are visually represented in results GUIs, and some are generated as downloaded files. These performance measurements are very valuable for the evaluation purposes such as to quantify, compare, verification and validation etc.

Few common performance indicators are briefly explained below, and some more Egress performance representations including graphical representations are provided in Appendix C for further reference.

- **Total Evacuation Time:** This is the time taken for all occupants to complete the evacuation (or all their assigned behavior tasks) which displays in the Simulation run GUI
- **Evacuation timeline and exited occupant count:** In the Simulation run GUI, there is a timeline and exited occupant count display, visualized dynamically throughout the simulation run.
- **CSV files:** Once simulation is run, these files are generated and downloaded into a separate folder which includes much information in the columns of Excel files. for example, room-wise remaining occupant counts, Occupant coordinates (x,y,z) over time and exited occupant count etc. See Figure: Appen. D. 18 (in appendix D) for a sample CSV file

7.5 Benchmarking, Verification and Validation

The Verification and Validation are very fundamental requirements of Egress Simulation software. It confirms the usability in real practice and builds-up trust with the user on the application which is essential in the context that deals with emergency.

Referring the IMO guidance on Egress Simulation tools, the researcher has conducted most of the specified tests simultaneously benchmarking wherever necessary with same tests conducted on another Egress Simulator (AnyLogic) available on the ARTICLE (Zhang, et al., 2022).

Further, the test numbering in this thesis report and Pathfinder files (valid only for test number 1 to 10) follow with the test numbering in the ARTICLE (Tests in its Appendix A) for the convenience of benchmarking. The test number 11 (also PF file) of this thesis will be benchmarked with the test found in Appendix B in the ARTICLE.

7.5.1 The Verification

The test number 10 [IMO test 11: Staircase (IMO, 2016)] is discussed here under verification while other tests are available in the Appendix D for further reference. (Test no 1 is already discussed above, refer figure 7.1 to 7.4)

Below in this sketch provided in IMO test 11: Staircase (IMO, 2016), only the width of the staircase is specified. But it doesn't specify about the dimensions of the steps. Therefore, researcher referred to the IMO website for the dimensions of the steps. (Limited, 2022)(section 4.9: Steps)

It says "*4.9.1 Steps are to have appropriate slope, spacing, width and size of tread. Wherever possible the slope for steps is to be 38° from the horizontal, with a tread height of 170 mm, a depth of 290 mm and step width of at least 710 mm.*"

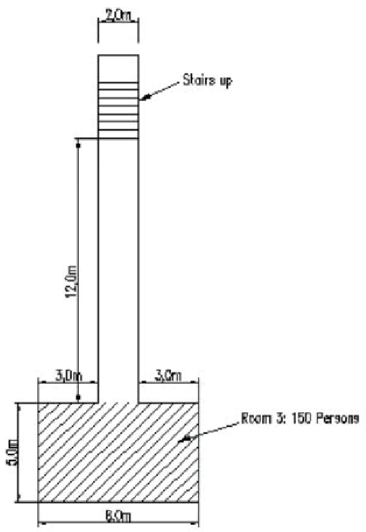


Figure 7. 5: The sketch for the IMO test 11: Staircase.

Referring the sketch and using the step details found, a Pathfinder model was designed including 150 occupants.

A new profile was created in PF, Male 30 – 50, specifying the speed characteristics to uniform distribution with 0.97 m/s and 1.62 m/s as the min and max speeds. It's necessary to aware that occupants follow SFPE speed fraction (from the speed of flat terrain) depending on the staircase angle which is also the default setting in PF. In addition, occupants were located uniformly in the room with random initial orientation and without initial delay.

Desired test results as specified in IMO test 11 is to have congestion at room exit, steady occupant flow in the 12 m corridor and formation of another congestion at the bottom of the stairway.

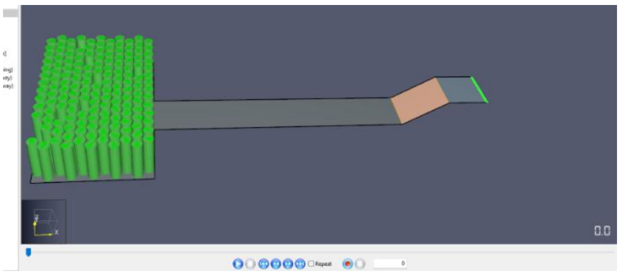


Figure7.6

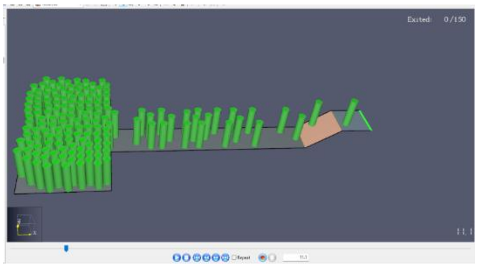


Figure7.7

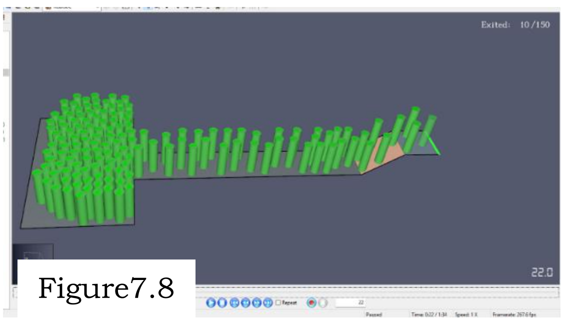
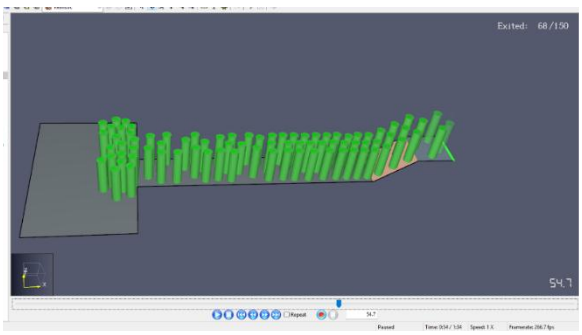


Figure7.8

Figure 7. 6: The view of occupants ready to start the simulation.

Figure 7. 7: The congestion at the exit of the room and a steady flow throughout the corridor can be observed.

Figure 7. 8: Gradual development of the congestion at the bottom of the staircase in addition to the congestion at the exit of the room and the steady flow in the corridor.



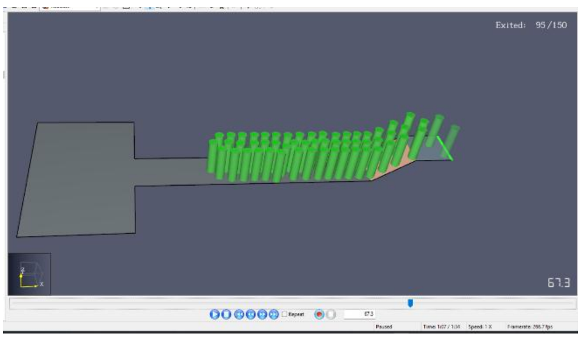


Figure 7. 9: Further congestion at the entrance of the stairway and spreading it backwards in the corridor.

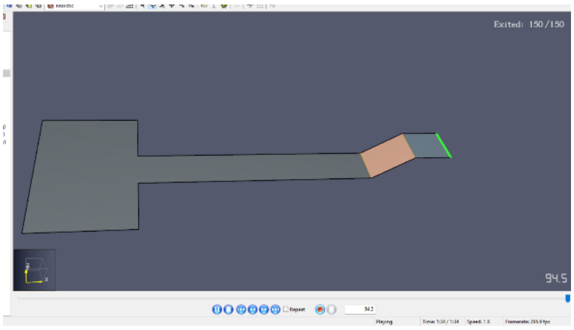


Figure 7. 11: It took 94.5 s to complete the evacuation as shows below

Pathfinder screen views are self-descriptive verifying the desired test results of IMO.

7.5.2 Benchmarking and Validation

The test 11 [{IMO: Quantitative Verification (IMO, 2016)}, ARTICLE: The test in Appendix B] is discussed here under validation.

This Pathfinder test attempts benchmarking with the test given in the ARTICLE while ARTICLE has referred a real-life demonstration conducted with 240 sophomore girls in a dormitory, presented in (Lei, et al., 2012). So, it is a comparison between a real-life demonstration and 2 Egress Simulators (AnyLogic and Pathfinder).

First, it is required to model the dormitory in Pathfinder to run the evacuation simulation. But the challenge was lacking information about the dormitory dimensions. Only one sketch with just 2 measurements as shown in figure 7.12 was available on the article that presented the evacuation demonstration (Lei, et al., 2012). Some of much important information like cabin sizes, cabin exit door dimensions, evacuation corridor dimensions, building exit door placement etc. were missing. So, the only possibility was to use this plan view as the background image of Pathfinder model and the special technique (using another extra supportive Pathfinder model) that was used to overcome the challenges and other important modelling aspects are explained in Appendix E.

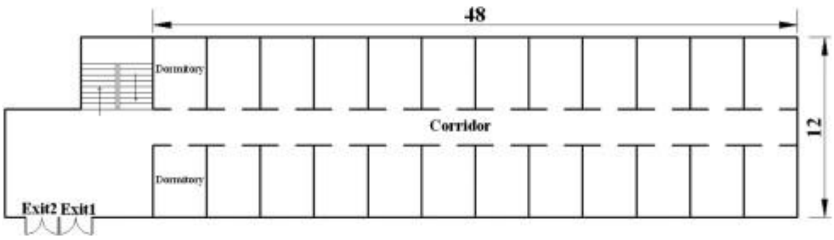


Figure 7. 12: Plan view of dormitory (Lei, et al., 2012).

As a part of the same evacuation demonstration, those researchers also had modelled a simulation in **FDS+Evac** software (Lei, et al., 2012, p. 5189). They had tested that **with and without pre-movement time taken as 0 – 30 s.** In addition, **average free movement speed of students had been observed as 0.73 m/s** in the experiment and then **the evacuation speed of occupants in FDS+Evac simulation had been set to 0.6 – 0.8 m/s** (Lei, et al., 2012, p. 5192).

The pre-movement time is called the initial delay in the **Pathfinder** software and that was set in the default behaviour setting "go to any exit", to a uniform initial delay of minimum 0 s and maximum of 30 s to all occupants like that was done in FDS+Evac simulation. In addition, in the Pathfinder, same evacuation speed range of

FDS+Evac, 0.6 – 0.8 m/s, was given to make results comparable between two software. Likewise, two Pathfinder simulation results were obtained, with and without initial delay for the same speed range.

In the **AnyLogic** simulation for the test of Appendix B in the ARTICLE, it is not stated either initial delay is used or not for the occupants. They have given another **speed range for the occupants, 0.95 – 1.35 m/s**. To compare this simulation, speed range of occupants of Pathfinder was changed to same speed uniform range of 0.95 – 1.35 m/s. Here again 2 scenarios were made with and without the uniform initial delay of range 0 – 30 s.

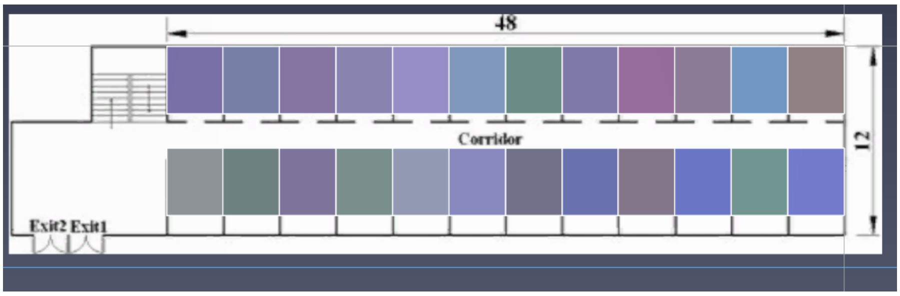


Figure 7. 13: View at the end of modelling 24 rooms.

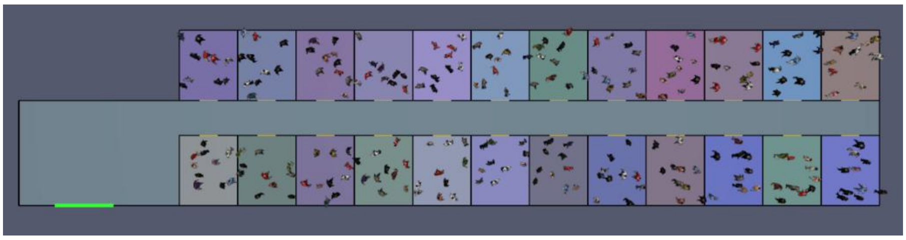


Figure 7. 14: Every room has 10 occupants

Occupants are oriented randomly in any direction. This is the initial positioning before running the simulation.

Figure 7. 15: Steering mode view

In the steering mode, occupants move relatively scattered to each other.

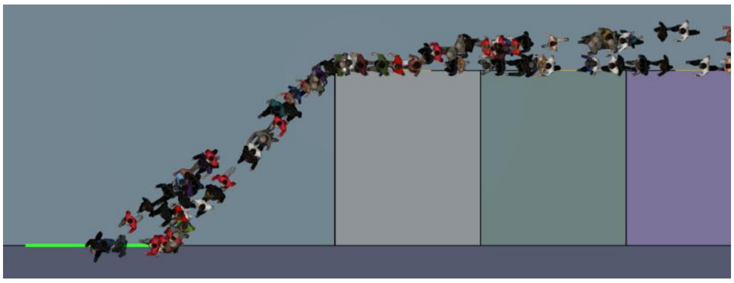


Figure 7. 16: In SFPE mode

Occupants move one after the other.

7.5.2.1 Results

All results are tabulated for the comparison as shown below.

	Experiment results	Pre-movement time	FDS+Evac	AnyLogic*	Pathfinder - Stearing Mode		Pathfinder - SFPE Mode	
			Speed (m/s)		Uniform Speed (m/s)		Uniform Speed (m/s)	
			0.6-0.8	0.95-1.35	0.6-0.8	0.95-1.35	0.6-0.8	0.95-1.35
Arrival time of the first student (s)	9.2	With	12.2	11.3	19.3	12.5	17.6	11.4
		Without	6.64		16.1	10.2	14.8	8.7
Mean evacuation time (s)	81.7	With	82.73	85.1	100.8	67.8	73.5	54.1
		Without	77.29		91.4	59.6	63.8	46.2
Total evacuation time (s)	154.2	With	156.25	156.2	174.7	115.8	120.7	94.4
		Without	143.65		164.5	108.2	108.2	88.6

* Use of pre-movement time (Initial delay) in AnyLogic software simulation is not mentioned in the ARTICLE

Table1: Evacuation times are shown under different categories to compare evacuation demonstration (experiment) and 2 other software in different speeds, modes and with/without pre-movement time (initial delay).

	Experiment results	Pre-movement time (Uniform 0-30 s)	Pathfinder - Steering				Pathfinder - SFPE			
			Uniform Speed 0.6-0.8 (m/s)	Relative Error %	Uniform Speed 0.95-1.35 (m/s)	Relative Error %	Uniform Speed 0.6-0.8 (m/s)	Relative Error %	Uniform Speed 0.95-1.35 (m/s)	Relative Error %
Arrival time of the first student (s)	9.2	With	19.3	110	12.5	36	17.6	91	11.4	24
		Without	16.1	75	10.2	11	14.8	61	8.7	5
Mean evacuation time (s)	81.7	With	100.8	23	67.8	17	73.5	10	54.1	34
		Without	91.4	12	59.6	27	63.8	22	46.2	43
Total evacuation time (s)	154.2	With	174.7	13	115.8	25	120.7	22	94.4	39
		Without	164.5	7	108.2	30	108.2	30	88.6	43

Table 2: Evacuation times and relative errors are shown under different Pathfinder modes and speeds with/without pre-movement time (initial delay) to compare with evacuation demonstration (experiment).

Below 2 graphs were generated from PF results analysis that present the occupants' usage of the exit doors against the time.

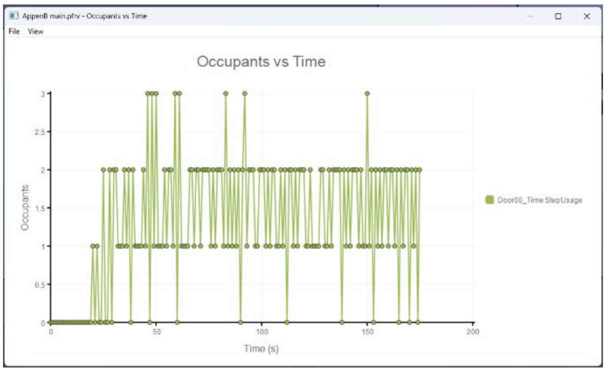


Figure 7. 17: The usage of exit door 0 against the time.

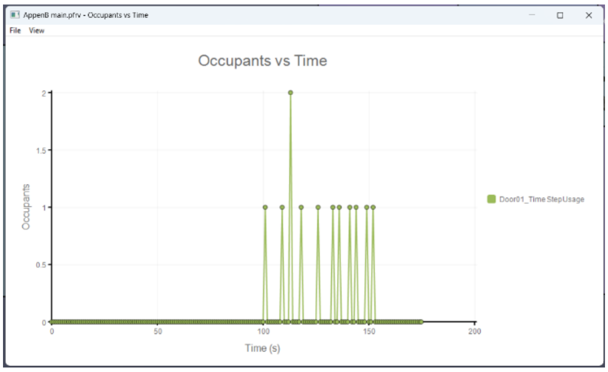


Figure 7. 18: The usage of exit door 1 against the time.

The exit door 1 of PF (Door 2 in the experiment) is used by only 12 occupants while all other 228 occupants have exited through exit door 0 of PF (Door 1 in the experiment). So, it doesn't reflect a congestion at the 2 exit doors in PF simulation.

7.5.2.2 Discussion

- There are 2 benchmarking possibilities in this test due to the availability of two other software (FDS+Evac and AnyLogic). There are 8 comparison combination with Pathfinder [I.e. FDS+Evac with AnyLogic in 2 Pathfinder modes (steering & SFPE) and with and without pre-movement time]. The relatively closest time combination can be seen in FDS+Evac with Pathfinder in steering mode without the pre-movement time. This relative result closeness can be explained as of due to the close parameter settings (speed, no pre-movement and more exits through doors in steering mode).

- When comparing experiment data with Pathfinder results in the validation perspective, relatively closer results than others can be seen with Steering mode, without pre-movement time and speed range 0.6 – 0.8 m/s combination. Still first student's arrival time has a higher relative error.
- There may be many reasons that might have affected these deviations. The possible design variations due to lack of availability of building dimension might affect directly, as room doors (24 times), walking corridor and exit door placement are much sensitive lacking information that has more influence on Egress Simulation. In addition, there are many other information just default values were used due to the unavailability of information (such as occupants' sizes) which can also has influenced the said variation.
- Usually, a dormitory for students is a very familiar place they possibly spend a longer time there. This might be the reason for all 3 experiment data values still lower than the said closest match of PF results.
- As it is stated in (Lei, et al., 2012) students were aware of the evacuation experiment and the videoing of the event and were specially prepared for the evacuation experiment with carrying a room number display board. All these aspects can simply direct to some over reactions ending the faster evacuation results with the lesser evacuation time in the real evacuation experiment.
- As it shows by the below picture from the real experiment sophomore students move more closer to each other, very much appreciating the general grouping effect of human behaviour.

Figure 7. 19: sophomore students evacuate from dormitory

(Lei, et al., 2012).

7.5.2.3 Sub Conclusion

- It can be concluded as worth to put effort on minimizing deviations by finding more information specially on those have direct influence in the Egress Simulation that has been named in the discussion section.
- Possible precautions must be taken to avoid the biasness of the experiment. It could otherwise be mis-interpreted as a mismatch of the simulator.

7.6 Sensitivity Testing (Monte Carlo Simulation)

Pathfinder has provided some limited facilitation by providing a set of scripts to run from the command prompt (a separate user manual is provided). This facility might useful for testing the sensitivity to initial conditions (starting position, profile parameter assignments) and to validation of distributions (Normal, Uniform, log-normal).

7.7 Hazard Representation

Pathfinder itself has not provided inbuilt facility to develop Hazardous conditions like a fire because its focus is on the egress section. The best facilitation provided at present to serve this purpose is to connect with PyroSim - another software by the same developer – which is another GUI for the Fire Dynamics Simulator (FDS) version 6.9.1 (Thunderhead Engineering, PyroSim, 2024).

Anyway, Pathfinder has considered the possible effects and consequences of hazards (mainly on the fire related and its effects such as smoke and heat) in its development of PF capabilities. So, PF has provided some parameters for both occupants and other objects like obstacles to depict the effects of hazards such as low visibility in smoke. More Examples are provided in Appendix F.

Chapter 8: Discussion

The Pathfinder facilitates the building up of spaces that is to be represented as the evacuation environment in real scenario. It builds rooms, corridors, stairs, obstacles, doors and exits doors etc.

It also facilitates the development of Occupants with many characteristics provide to them which makes user's convenience of working with it. In order to imply the age and gender, it can make profiles named giving the similar meaning then the characteristics must be manipulated to represent the capabilities which is as of the choice by the user. Most important features like speed, flow rate through doors are already available.

Activities are to be defined by behaviors and many behavior options are provided. Not only the usual "use any exit" but special activities like assisted evacuation. Pre-movement delay or initial delay is one another important and widely used feature already available in Pathfinder.

It has provided many egress performance evaluation indicators in many forms not only in quantification means like egress time but also qualitative visual representations like colour associated heatmaps.

Stochastic features also available in distributions such as normal, uniform and basic sensitivity analysis possibility is also given with limited features.

Pathfinder has provided dynamic decision making like changing the exit door when congestion is available is another feature available at present.

Pathfinder can be verified and validated using its test results

Challenges and areas to improve

Pathfinders provides basic manual sketching tools in its modelling GUI, but complex designs are to be imported working from other software is a limitation that can be developed in future.

It can also include the differentiation of recognition and response time within its initial delay feature as it is commonly discussed in the egress timeline approach, which is another improvement factor to be recommended.

Pathfinder can also improve on its sensitivity analysis tools where it provides only very basic facilitation at present. For example, the model geometry can not be tested for sensitivity at present.

Chapter 9: Conclusion

Pathfinder as an egress simulator there are many fundamental requirements and features available in it which supports the Egress Simulation.

Egress and Egress Simulation are commonly discuss explaining with the theories like Egress timeline approach and Emergency Management Principles frequently.

Pathfinder can be used to depict real-world entities such as buildings, humans and their characteristics and behaviours that has been represented in this research in modelling some IMO recommended test.

These tests were verified benchmarking by the results found from the ARTICLE.

Validation can also be done similarly but necessary information is a pre-requirement.

Pathfinder's many capabilities and features are very useful in depicting real-world egress simulations is a great advantage. Its disadvantages mostly a challenge that can be overcome with some effort and resources. Some limitations like limited capability in manual modelling can be improved.

Chapter 10: References

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Appendix A

Pathfinder has many occupant profile characteristics. Few of them have been selected below that simultaneously represents some of available features and capabilities of Pathfinder.

- **Reduction Factor:** In crowded situations occupants squeezed themselves letting others to move. This setting is important since it replicate a natural human behaviour.

- **Polygon:** Occupant is getting another mode of transportation such as a wheelchair or a stretcher bed. Example: This can be used to represent a patient lying in a bed.

- **Requires Assistance to Move**: Occupant waits until another occupant assists to move. Useful when evacuating a patient etc. In assisted evacuation**.**

- **Ignore One-way Door Restrictions**: Occupant will ignore one way door restrictions, useful for some special occupants having special rights such as a doctor or a policeperson etc.

- **Acceleration Time:** This is a Steering Mode parameter that specifies the amount of time it takes for the occupant to reach maximum speed from rest or to reach rest from maximum speed. This setting is important since it replicate a natural human behaviour.

- **Personal Distance:** The desired distance one occupant will try to maintain with others in a queue. This setting is important since it replicate a natural human behaviour.

- **Social Distance Occupants:** Enables or disables Pathfinder's social distancing model for the occupant profile and indicates which occupants should be used to apply "Social Distance". Social distancing was frequently used in situations like pandemics. This feature enables to selected occupants perform with social distancing.

- **Speed in Smoke:** When FDS Output integration is enabled, this option controls how much smoke will limit the maximum velocity of occupants. Evacuation speed gets affected with the presence of smoke and this parameter is important in replicating performance in smoke.

Appendix B

Pathfinder has many behavior actions for the occupant to perform in the simulation. Below shows few of them that simultaneously represents some of available features and capabilities of Pathfinder.

- **Goto Waypoint:** Asking the occupant to move to a specified location. User can define the location (Example: Assembly point) as required within the occupant movement space.

- **Goto Queue:** Asking the occupant to join a designated queue. (Example: Asking occupants to gather to different platforms in a railway station.)

- **Wait:** Asking the occupant to wait at the same current location for a specified time

- **Change Profile Property:** Asking an occupant to change one of the properties to a specified value. (Example: Change the set speed of occupant, like first walking and then running)

- **Create/destroy Trigger:** Asking an occupant to create/destroy a trigger that may influence other occupants. (Triggers are usually used for example as Alarms. So, this can be used to start and stop alarms.)

- **Assist and wait for assistance:** Asking an occupant to assist another occupant, similarly other one is asked to wait for the assistance. This is frequently used to simulate assistance services for example a flight attendant helping an elderly person in an airport.

- **Wait Until Simulation End:** Asking the occupant to wait at the current location until the end of the simulation

- **Goto Refuge Rooms:** Asking the occupant to go to a room designated as refuge area

There are also some behaviors that are associated with random selections from an assigned distribution. Following shows examples for this type.

- **Change Behavior:** Asking an occupant to change to a new behavior picked randomly from a behavior distribution

- **Change Profile:** Asking an occupant to change to a profile selected randomly from a profile distribution

Appendix C

Few, commonly used Egress performance indicators briefly explain below including some graphical representations.

- **The Summary Report:** A Summary Report is provided in the modelling GUI immediately after running the simulation which summarizes some commonly used information for example occupants total travel distance (includes details like minimum, maximum, average and std. Deviation).

Occupants Speed Visualization

In Pathfinder results viewer occupants' dynamic speed variation is visualized including a colour coded legend explanation. User can also activate "show occupant paths” view option that shows the trajectory combined with colours to represent speed variations. (see figure: Appen. C. 1)

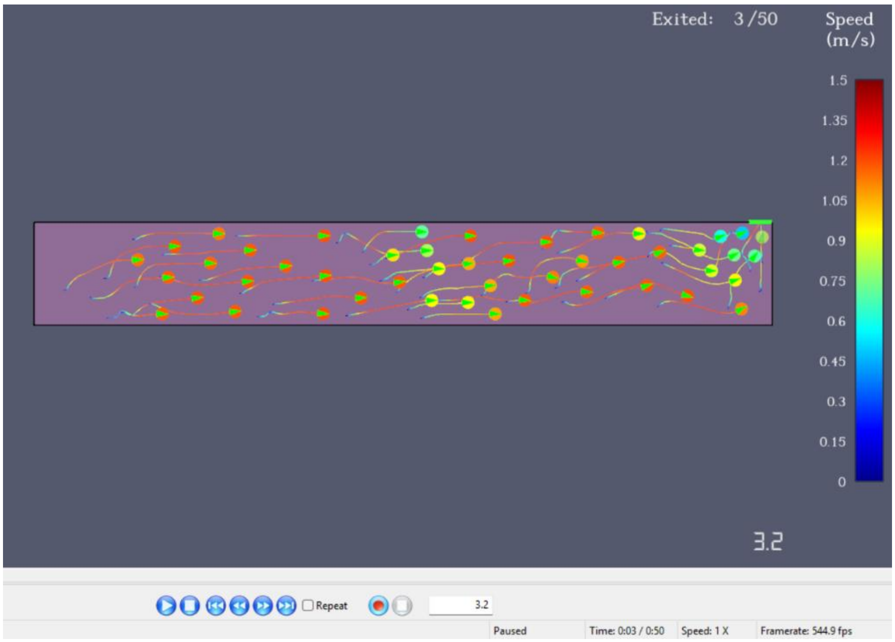


Figure: Appen. C. 1: Occupant trajectory and colour variation to indicate the speed changes.

9.5.3 Occupant density and Congestion Based Egress Performance Indicators

Occupant density heatmaps are used in Pathfinder to indicate the occupant density and congestion status in the results viewer GUI. It provides also the colour legend that user can visualize the congestion variation through colour changes.

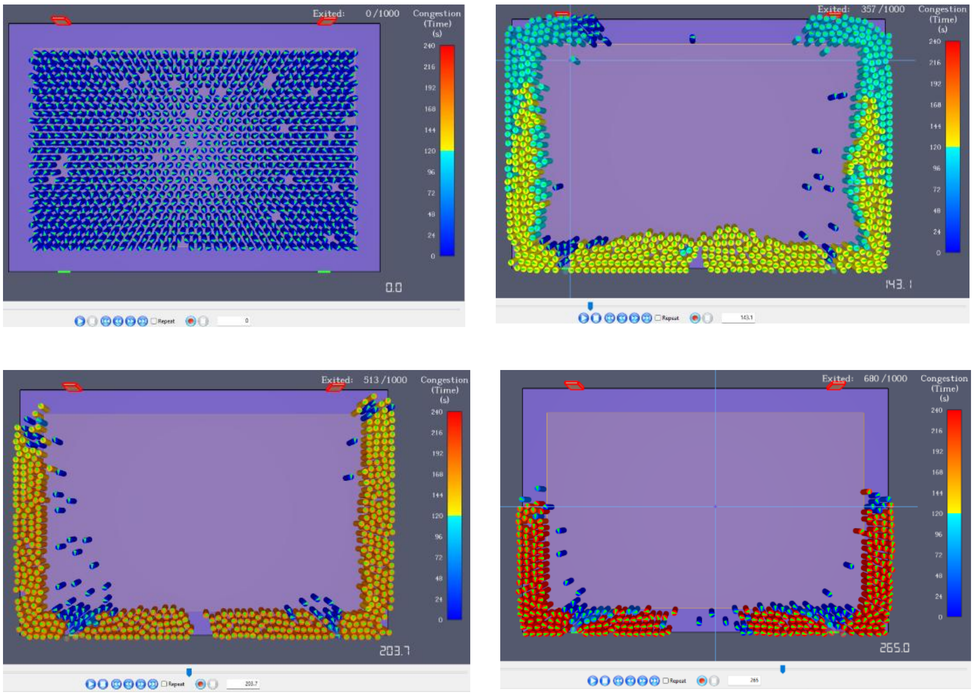


Figure: Appen. C. 2: Occupant density heatmaps

In addition, user can also designate some **Measurement Regions** in the occupants' navigation area which causes the simulator to output some time-history data (CSV file) on occupant speed and the density.

Congested areas and Level of Service (LOS) Contours

There is an occupant colour based qualitative congestion indicator that presents through Level of Service contours, based on Fruin's levels (A to F) as the colour legend. See below picture as an example.

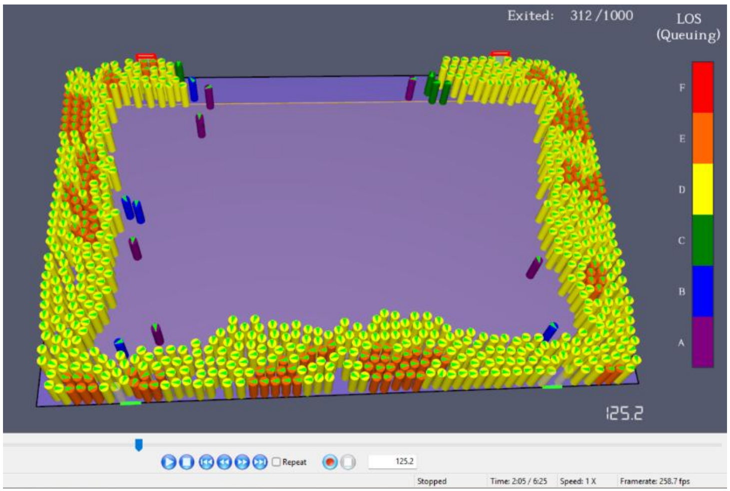
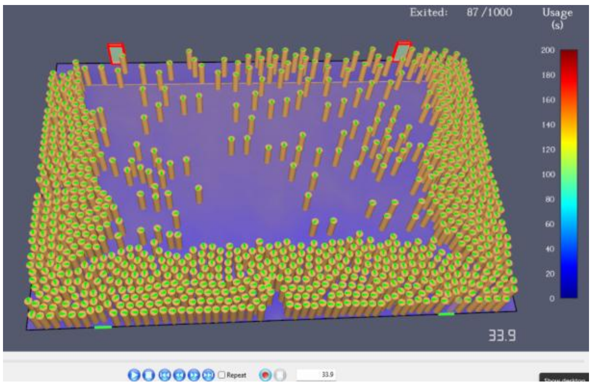
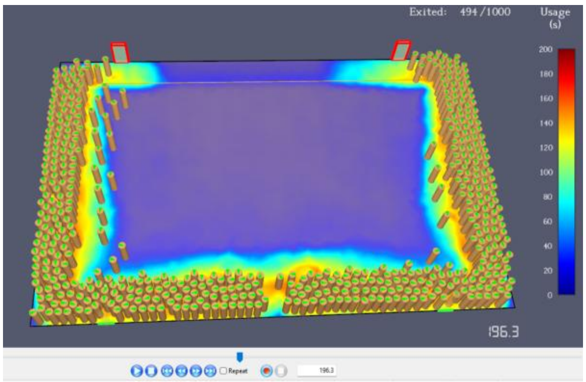


Figure: Appen. C. 3: Level Of Service shows in the figure

Occupant Contours / Heat Maps

Pathfinder provides qualitative and dynamic visualization of occupant data on the floor area in the results GUI. Colour legend is also associated as the relative quantification tool. See below picture which shows the accumulated floor usage of occupants (unit: seconds)





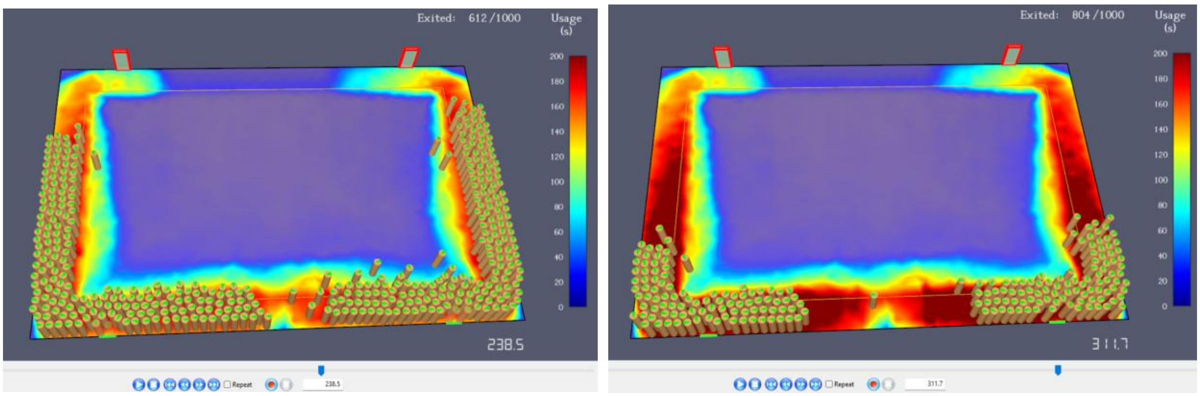


Figure: Appen. C. 4: Occupant contour heatmaps show in above 4 pictures.

9.5.4 Flow and Throughput Based Performance Indicators

Door Flow Rate: Pathfinder measures the occupant count passes through a door (including exits) per unit time and results are output in the column "Time Step Usage" of the door CSV file. In addition, in the modelling GUI, PF has an inbuilt drop-down menu to visualize as graphs of occupants' door usage per unit time (door flow rate) as shown below.

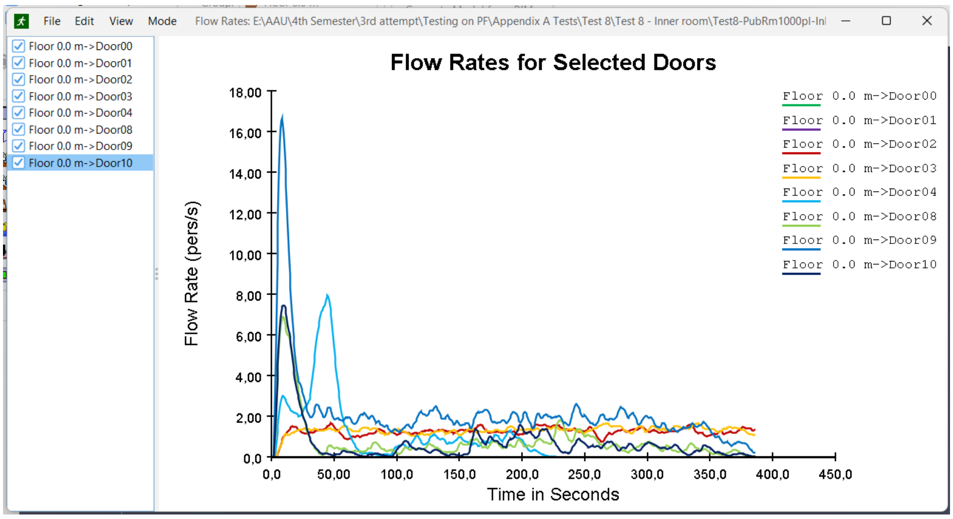


Figure: Appen. C. 5: Flow rate for selected doors

Specific Flow (Normalized Flow): Door width is an important concern when considering the door flow rate of occupants. Therefore, the specific flow rate or the flow rate normalized by the effective width of the door is used specially in comparison purposes. (Specific flow must be selected in Mode dropped down menu in results diagram view - see picture -, otherwise shows the default: Flow rate)

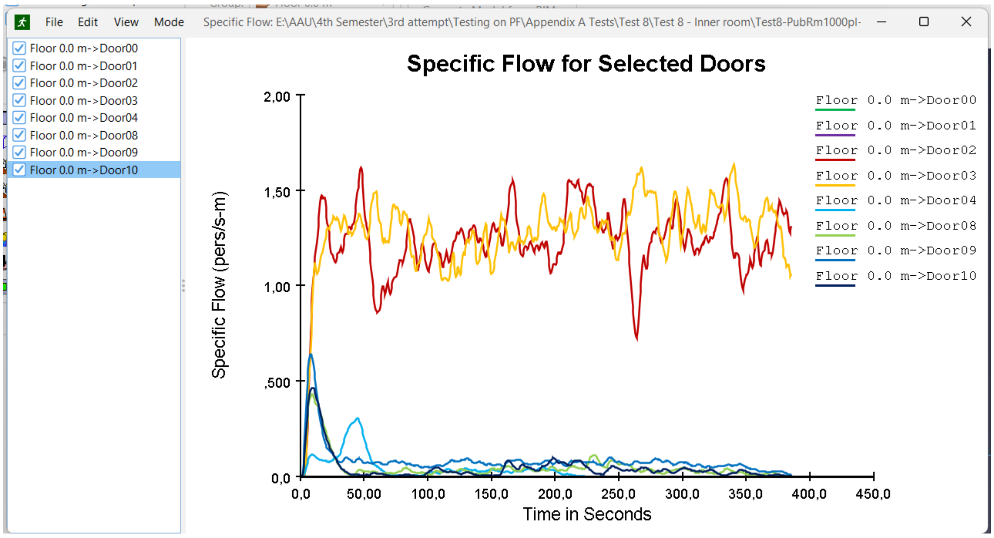


Figure: Appen. C. 6: Specific flow for selected doors

Throughput details in Summary text document: Pathfinder run results folder contains a text document (filename_summary.txt) that contains the summary report of the simulation which provides the aggregated usage statistics for each door, stair and room in the simulation environment. This summary document lists **"First In"** (time when First occupant entered), **"Last Out"** (time when last occupant passed) and **"Total Use" (**how many times occupants passed through) for every object. So, user has given the provision to derive further analysis (Ex: average flow) using this information.

Queued Occupant at Exits in SFPE: In SFPE mode Pathfinder records the number of people waiting in the queue to exit at each exit door at each time step in a column called **"Queued Occupants"** in the doors CSV file. User can use this information in further evaluations for example in crowd management etc.

9.5.5 Simulation modes and Output Formats Based Performance Indicators

Steering and SFPE: As it is explained above, Pathfinder provides these two simulation modes that user gets the opportunity and convenience of changing and experimenting between these two modes in the same simulation model.

Pth, CSV, Txt and Json files: As it has been discussed above Pathfinder outputs - 3D Pathfinder files (.pth), for modelling and results visualization. In addition to these, PF outputs result also on text documents summary files (.txt), Microsoft Excel Comma Separated Values (.csv) and the latest version is included with JSON (JavaScript Object Notation) file which provides user the easier programmatic access.

Appendix D

Test 2: Observing set speed for moving up stairs

A staircase was developed between 2 stairs (horizontal distance 7.8801 m apart and the height of 6.1388 m to get the tangential distance of 10 m for the staircase, having angle 38^0 for the horizontal as the guidance by IMO). A single person was placed in lower floor and assigned the exit on the upper floor. Walking speed of the person is set to 1 m/s for flat terrain and for stair up movement and orientation was set to 0^0.

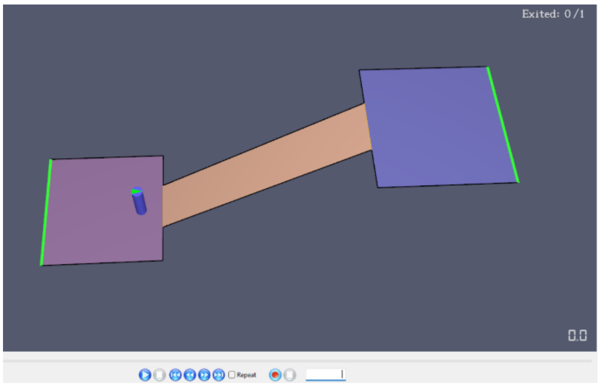


Figure: Appen. D. 2: Initial position, 0 s.

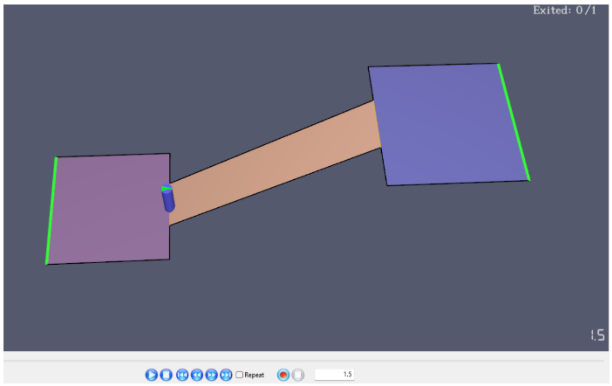


Figure: Appen. D. 1: Occupant enters staircase, time is 1.5 s

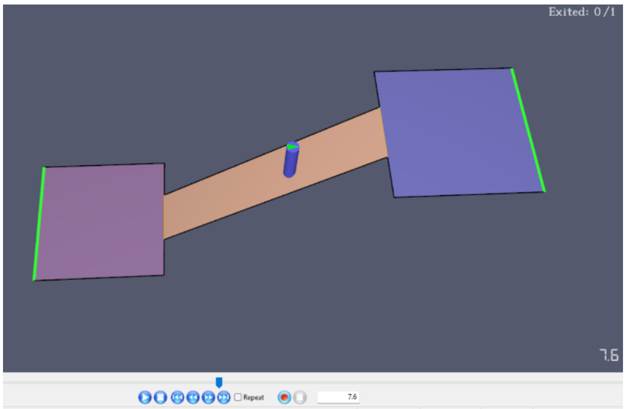


Figure: Appen. D. 4: Occupant moves up the staircase, time is 7.6 s

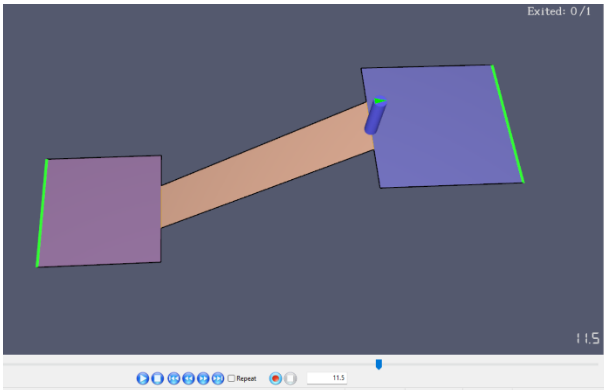


Figure: Appen. D. 3: Occupant is about to leave the staircase, time is 11.5 s

3D Graphical views confirm that occupant has taken 10 s (= 11.5 – 1.5 s) to walk through the staircase. This walking time is appreciated as when occupant has the set walking speed of 1 m/s and staircase length is 10 m. This verifies that occupant maintains the set walking speed walking up on the staircase in Pathfinder.

Test 3: Observing set speed for moving downstairs

Same staircase model used with some changes to the occupant to move from top floor to down floor. Occupant was assigned the exit on the down floor in behavior settings. Similarly, like previous test, the speed was set to 1 m/s constant. Occupant display was changed to people view in Simulation run GUI.

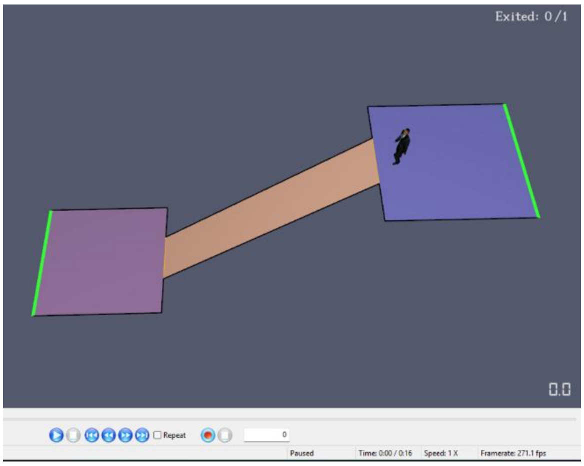


Figure: Appen. D. 6: Initial position, 0 s.

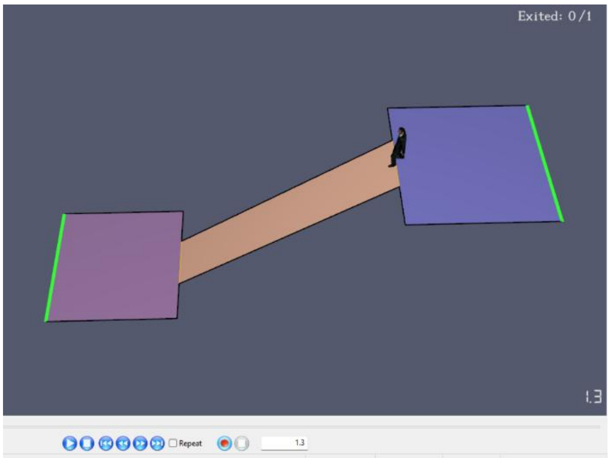


Figure: Appen. D. 5: Occupant enters staircase, time is 1.3 s

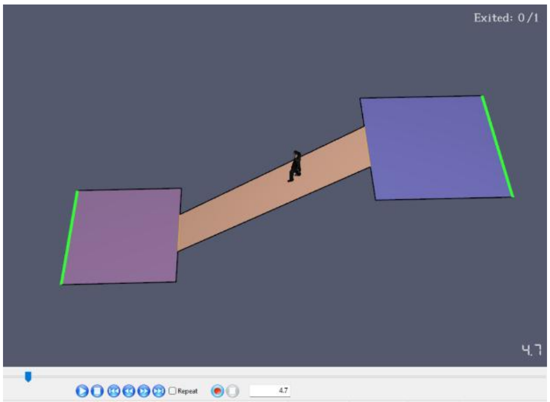


Figure: Appen. D. 7: Occupant moves down the staircase, time is 4.7 s

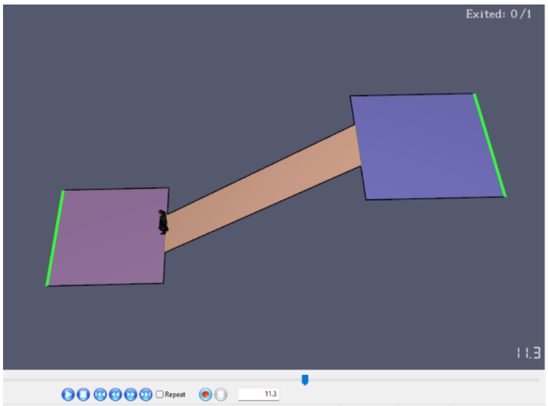


Figure: Appen. D. 8: Occupant is about to leave the staircase, time is 11.3 s

3D Graphical views confirm that occupant has taken 10 s (= 11.3 – 1.3 s) to walk through the staircase. This walking time is appreciated as when occupant has the set walking speed of 1 m/s and staircase length is 10 m. This verifies that occupant maintains the set walking speed walking down on the staircase in Pathfinder.

Test 4: Exit flow rate

One hundred occupants (p) located in a space of 8 x 5 m in size with a 1 m-wide door which is located on the middle of the wall of 5 m.

According to IMO guidelines "The specific unit flow rate for any exit should not exceed 1.33 p/m/s (IMO, 2016, p. 6 Anex 3)**".**

Below shows some steps of the design and evacuation run.

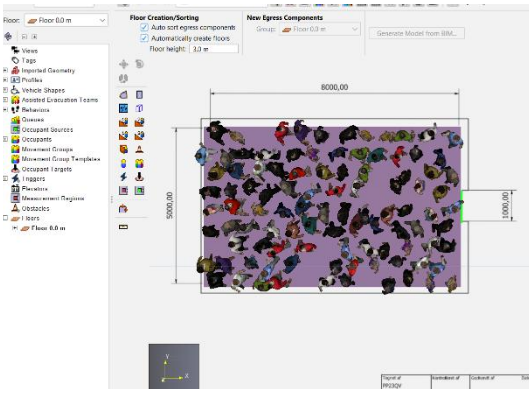


Figure: Appen. D. 10: Modelling is completed with 100 occupants in the room in Modelling GUI.

Figure: Appen. D. 9: Ready to start evacuation run in results GUI, time is 0 s.

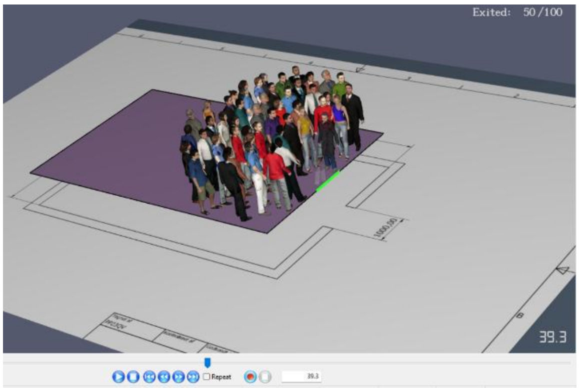


Figure: Appen. D. 12: 50 occupants evacuated. Evacuation time used is 39.3 s

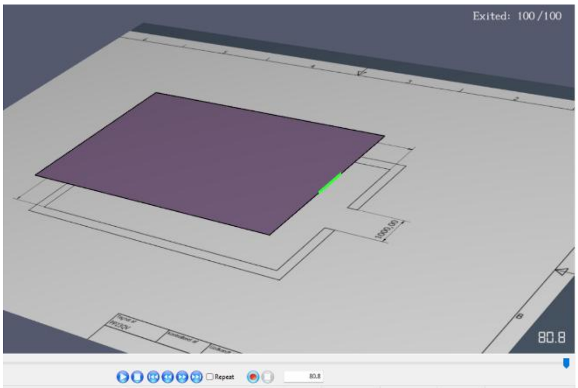


Figure: Appen. D. 11: All occupants (100) evacuated. Evacuation time used is 80.8 s

Pathfinder achieved specific unit flow rate in the test (considering the entire period in steering mode) = 100 (p) / [88.8 (s) x 1 (m)] = 1.1261 p/m/s. (< 1.33). So, this can be accepted following the IMO guidelines.

In the ARTICLE, testing on AnyLogic shows the results for the entire period as 0.73 p/m/s (Zhang, et al., 2022). So, when compared to AnyLogic, Pathfinder has a higher specific flow rate through the door in steering mode.

Though this Pathfinder evacuation can be accepted when considering the total evacuation, as shown in the below graph (Figure: Appen. D. 13), there are some instantaneous deviations beyond the 1.33 threshold. The explanation for this deviation finds with exit door flow rate default setting on Pathfinder which is unlimited and unchangeable in the steering mode.

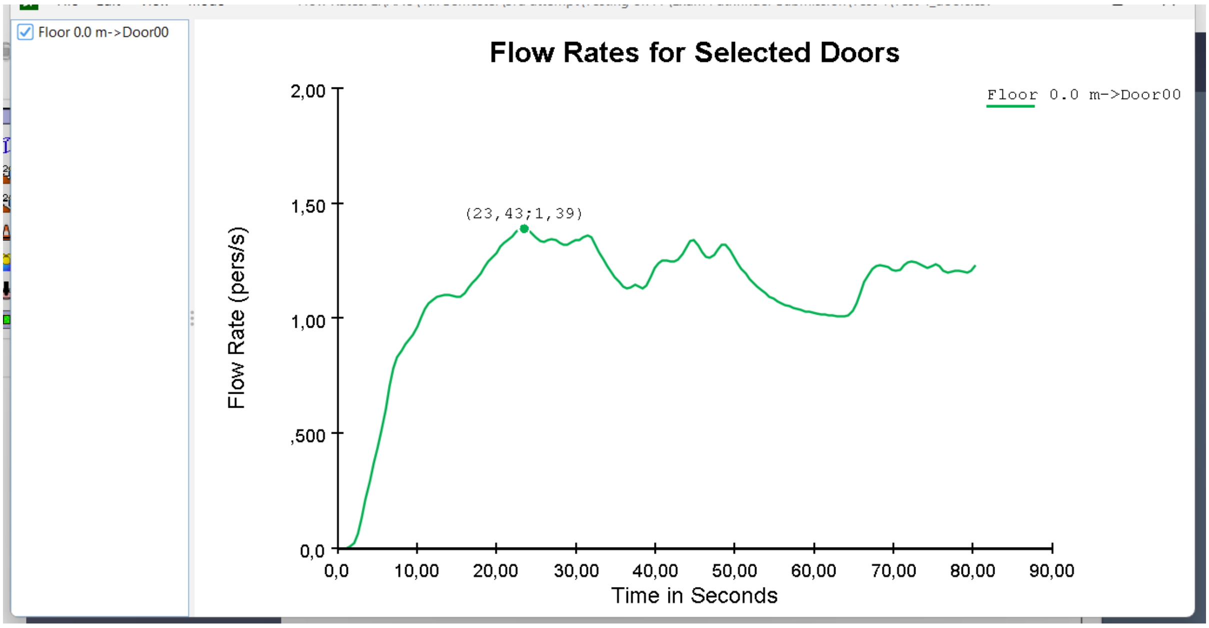


Figure: Appen. D. 13: Door flow rate value 1.39 > 1.33 (Steering mode)

Below graph is for the same model but for the SFPE simulation mode where flow rate through door depends on the occupant density, which shows a rate well below the threshold 1.33 value.

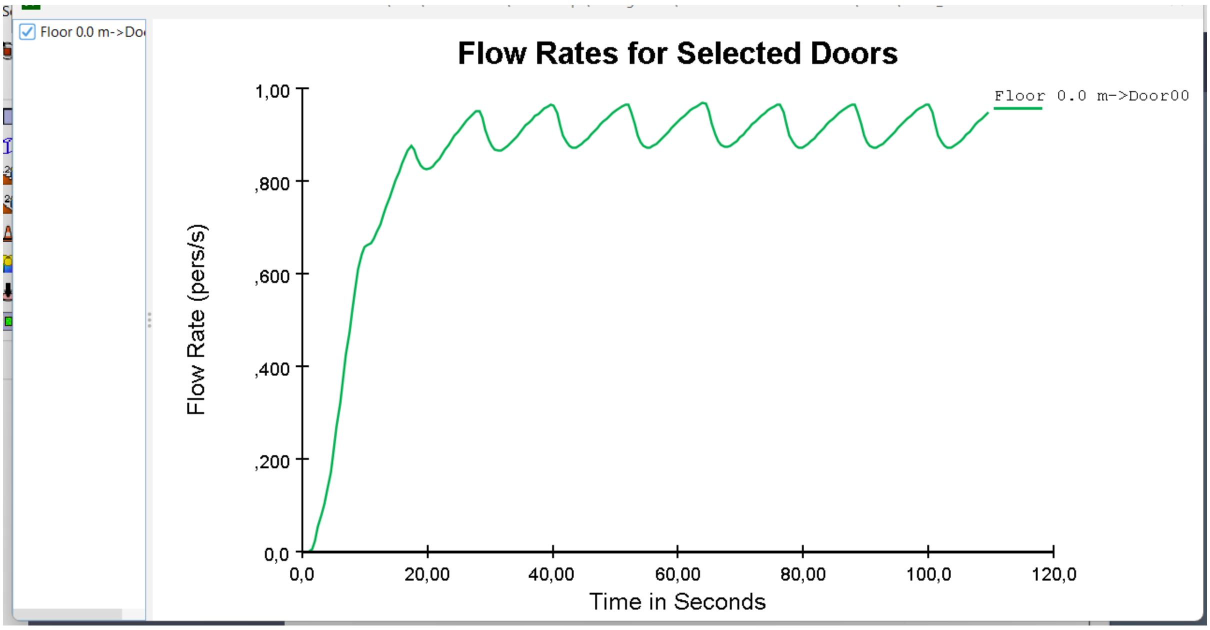


Figure: Appen. D. 14: Door flow rate value (SFPE)

Though IMO specifies on the 1.33 p/m/s threshold value, it is also important to highlight that IMO does not specify whether this is considering the entire evacuation or even instantaneous specific unit flow rate should be below 1.33 p/m/s. With this argument, this Pathfinder test can be accepted in this verification.

Test 5: Response time check (Initial delay of PF)

Here in the test 10 occupants were located randomly in a room of 8 m x 5 m having a 1 m wide door on one of the walls of 5 m. All of them assigned initial delay using one of the distribution facilities available in Pathfinder, which is Uniform with the minimum of 10 s and maximum of 100 s.

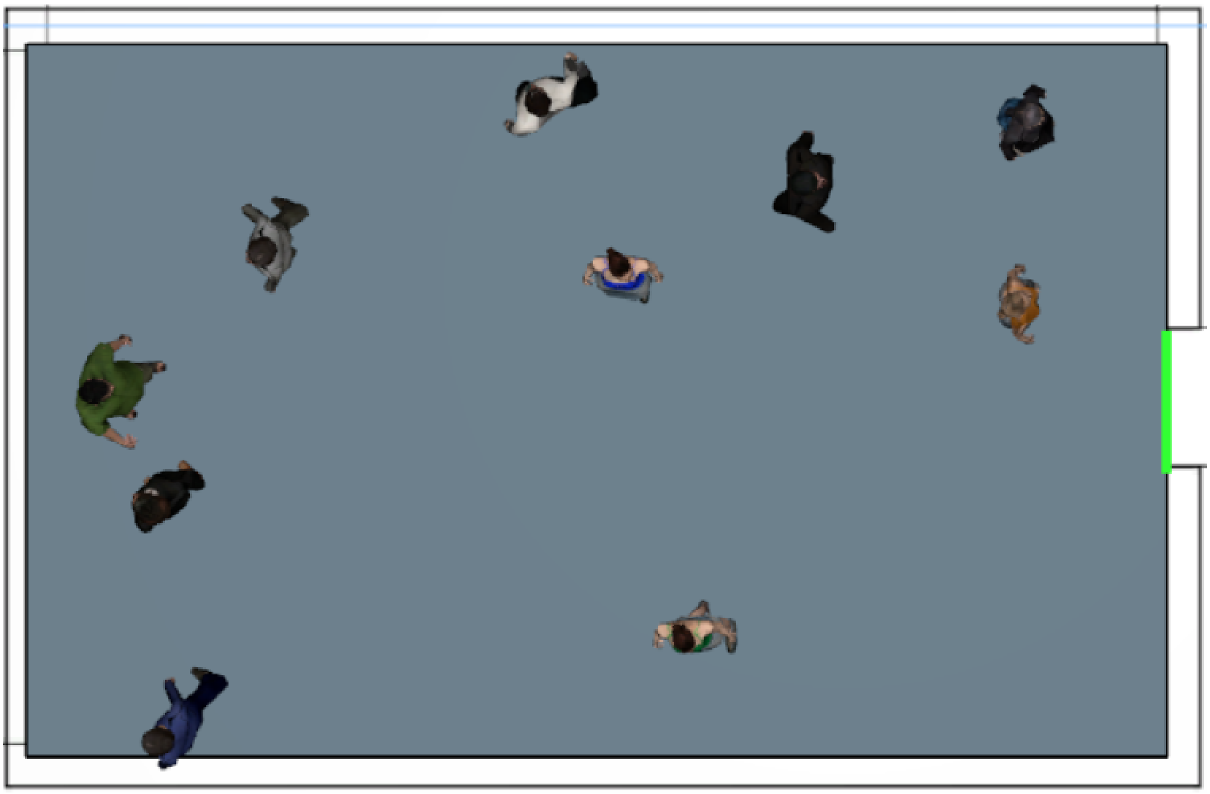


Figure: Appen. D. 15: Initial positions of occupants

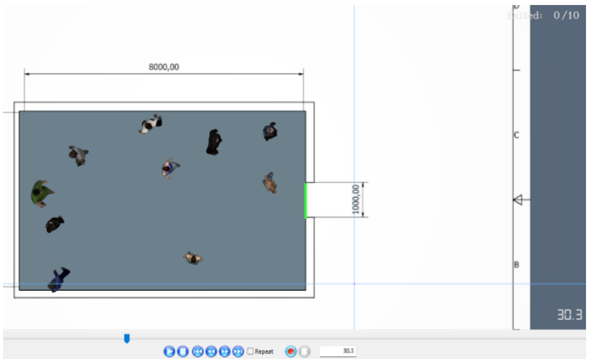


Figure: Appen. D. 17: 1st person started the movement at 30.3 s

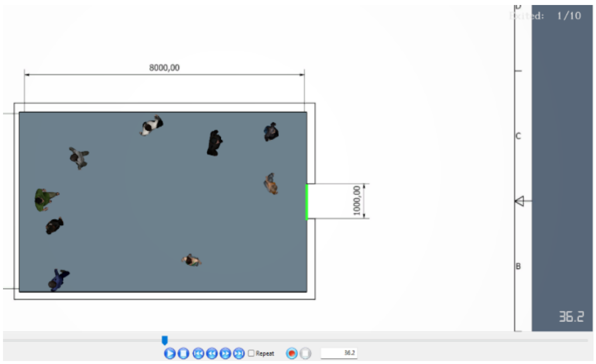


Figure: Appen. D. 16: 2nd person started the movement at 36.2 s

As expected, the 1st person should have been started movement 10 s and the 2nd at 20 s and likewise. But as shown in pictures initial delay does not obey the uniformity feature as expected in Pathfinder in steering mode.

id	name	exit time(s)	last_goal_started time(s)
0	3	33.925	29.85
1	4	58.8	52.875
2	5	43.375	37.425
3	6	102.75	95.55
4	7	87.1	84.075
5	8	101.85	99.35
6	9	71.5	69.925
7	10	42.625	35.75
8	11	44.4	36.25
9	12	73.75	70.2

Figure: Appen. D. 18: Initial delay information of all occupants from CSV file data

Since last goal is the evacuation movement, this shows the initial delay for all occupants. Initial delay time is not uniform as expected.

As per the information given in ARTICLE, same test on AnyLogic had presented the expected results.

Test 6: Rounding Corners

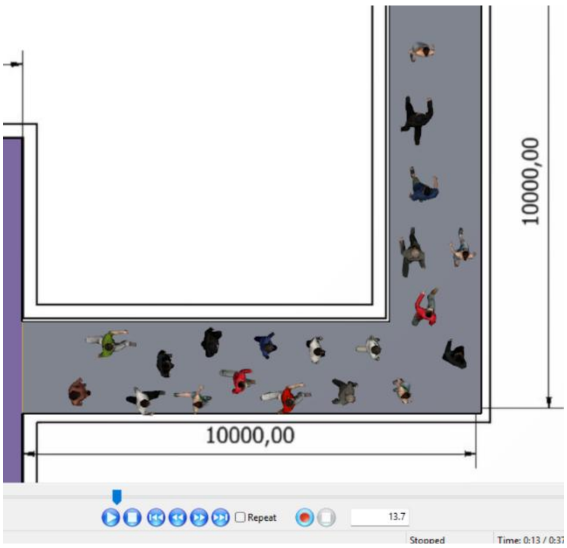


Figure: Appen. D. 19: Occupants move through left-hand corner

People do not penetrate the boundaries when navigating through left-hand corner.

This test verifies the expected results as specified by the IMO.

Same results were shown in the same test presented in the ARTICLE.

Test 7: Counterflow—two rooms connected via a corridor.

Four separate Pathfinder model were developed with two rooms of 10 m wide connected with 10 m long corridor between them. In all four models 100 occupants (Blue) were included in the room 1 and respectively 0, 10, 50 and 100 occupants (Orange) in the room 2. Both occupants assigned the same profile features and behaviors were assigned all occupants to move to the opposite side room to observe the counterflow reaction. Total time taken by last occupant from room 1 to move to room 2 was recorded.

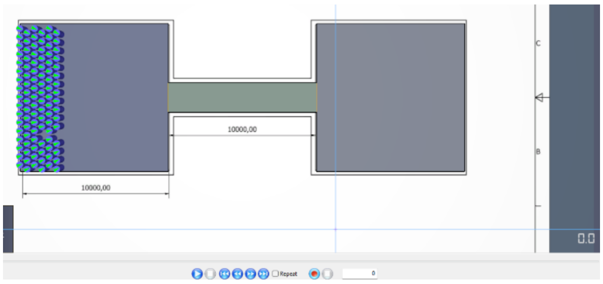


Figure: Appen. D. 21: Room 1 (only) has 100 occupants

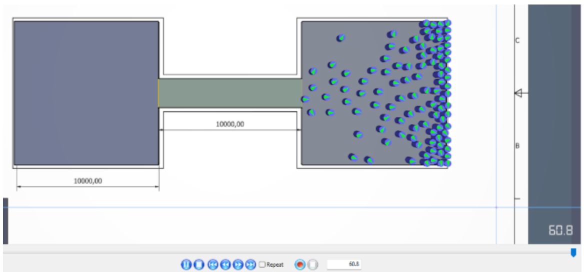


Figure: Appen. D. 20: Movement is over now. Total time taken is 60.8 s

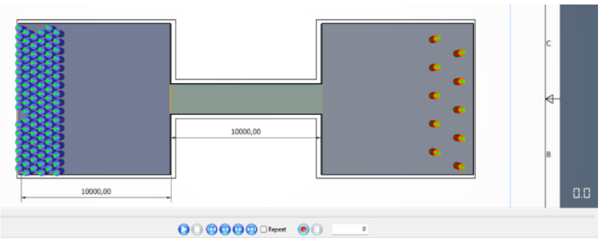


Figure: Appen. D. 23: Room 1 has 100 and room 2 has 10 occupants

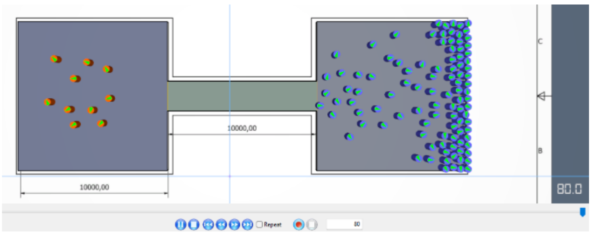


Figure: Appen. D. 22: Movement is over now. Total time taken is 80 s

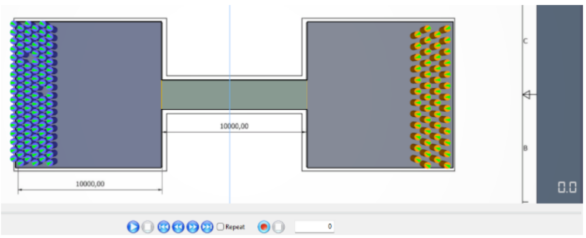


Figure: Appen. D. 25: Room 1 has 100 and room 2 has 50 occupants

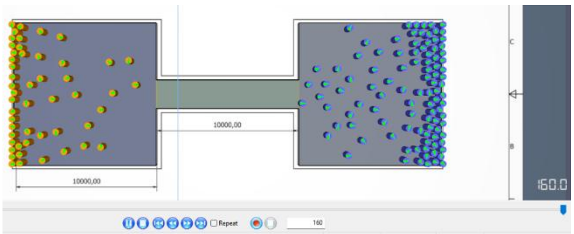


Figure: Appen. D. 24: Movement is over now. Total time taken is 160 s

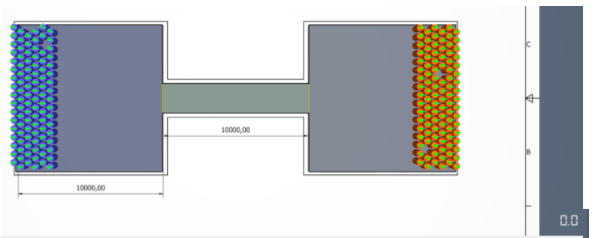


Figure: Appen. D. 26: Both rooms have 100 occupants in each

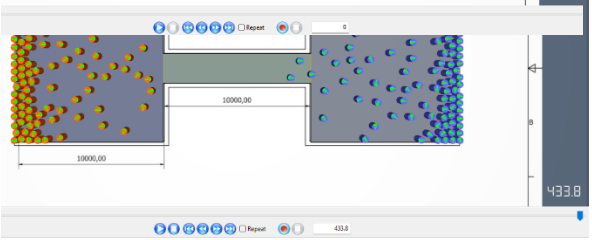


Figure: Appen. D. 28: Room 1 occupants still moving to room 2

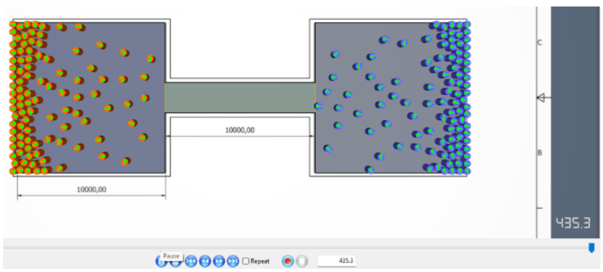


Figure: Appen. D. 27: Movement is over now. Total time taken is 435.3 s

Only 100 blue occupants: 60.8 s

100 blue occupants and 10 orange occupants: 80 s

100 blue occupants and 50 orange occupants: 160 s

100 blue occupants and 100 orange occupants: 435.3

It can clearly be seen that total time taken increases with the increase of the counter flow. So, verification can confirm that Pathfinder performs as expected in this counter flow test.

Test 8: Exit flow: crowd dissipation from a large public room. (Test 9 in IMO)

According to IMO test 9, 1000 occupants are uniformly distributed in a room (30 x 20 m) where in their initial positioning occupants ensure to maintain a gap of 2 m from all 4 walls inside the room. **There is a tool in Pathfinder "add occupants to a region" where user can specify the initial placement of occupants within a specific square region in a room.** Using this tool the required model was developed with 4 exits as specified in IMO test 9 in the Pathfinder, locating 1000 occupants initially in the 26 x 16 m square space.

A new Pathfinder profile is developed "males 30 – 50" representing males of age between 30 – 50 years assigned the speed characteristics of uniform distribution with min. speed 0.97 m/s and max. speed 1.62 m/s which was assigned to all 1000 occupants. All occupants have the same behaviour been assigned to them to go to any exit. "This behaviour simply makes the occupant move from their starting position to any exit present in the model by the fastest route."

Another test was conducted by shutting the door 1 & 2 with all other parameters keeping unchanged. (door characteristic was changed to "always closed")

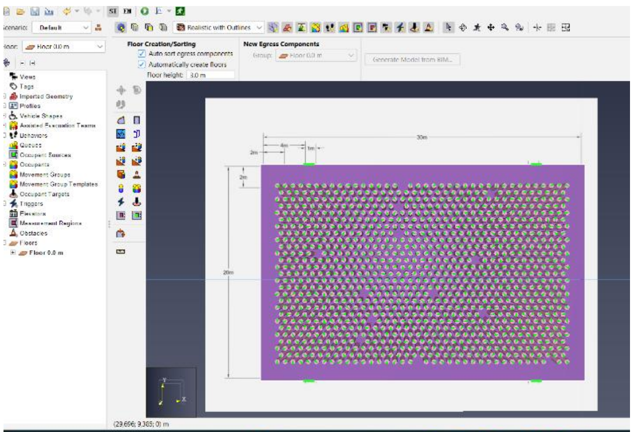


Figure: Appen. D. 29: View of modelling GUI at the end of modelling the test

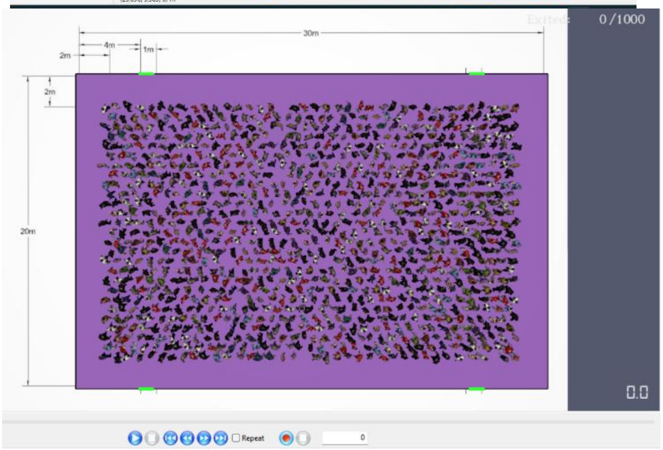


Figure: Appen. D. 30: Plan view of simulation GUI before starting the simulation.

Occupants are uniformly distributed maintaining the 2 m gap with all walls in the room. (4 exits)

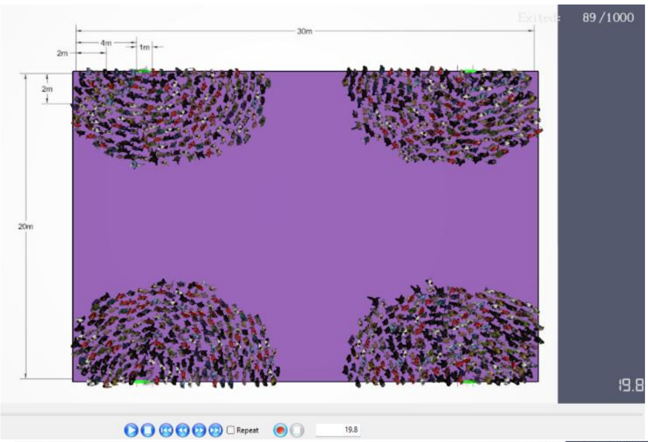


Figure: Appen. D. 31: Occupants gather in front of 4 exit doors in the below view.

89 occupants have exited.

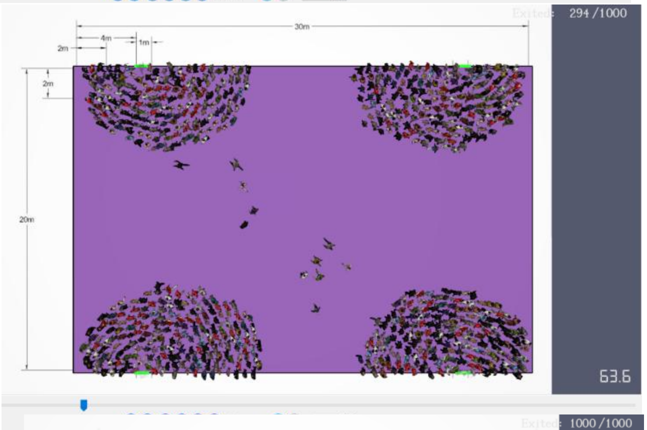


Figure: Appen. D. 32: Occupants change the exit door decision.

Occupants change the exit door decision in crowded situations. Here shows occupants (Pathfinder's) ability of dynamic decision making while simulation.

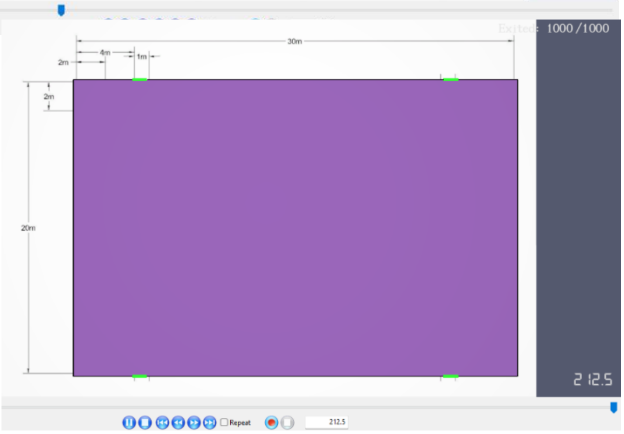


Figure: Appen. D. 33: All occupants exited.

It took 212.5 s to exit all 1000 occupants through 4 exit doors.

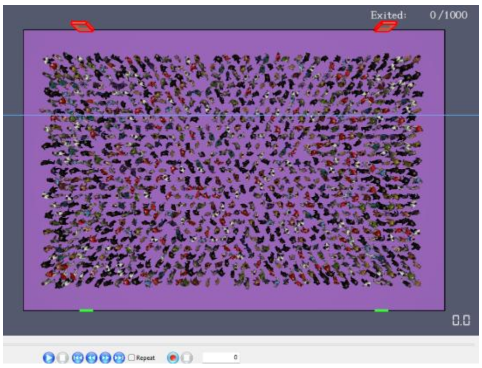


Figure: Appen. D. 34: 2 doors are always closed. (Initial position)

Above Pathfinder model used to initiate the designing of the new model and only the door characteristic was changed to "always closed" to both door 1 and 2.

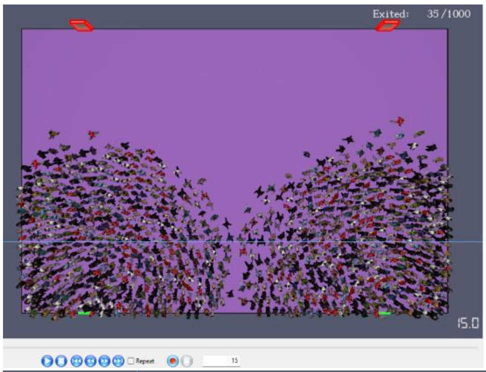


Figure: Appen. D. 35: Now occupants move only towards doors 3 & 4.

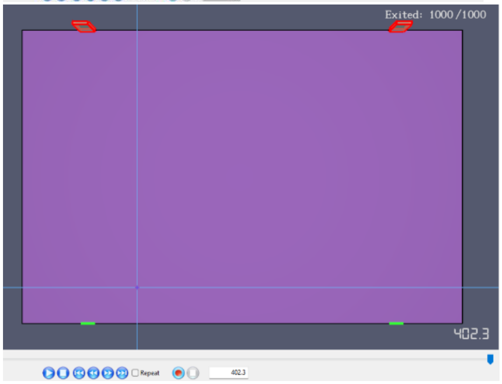


Figure: Appen. D. 36: All occupants exited. (2 door only)

When it was only 2 doors open, total time taken to exit all 1000 occupants was 402.3 s.

Time taken when 4 doors open = 212.5 s

Time taken when 2 doors open = 402.3 s

Time taken is almost doubled when only 2 doors were open. So, verification can confirm that Pathfinder performs as expected in this test.

Test 9: Exit route allocation (IMO test 10)

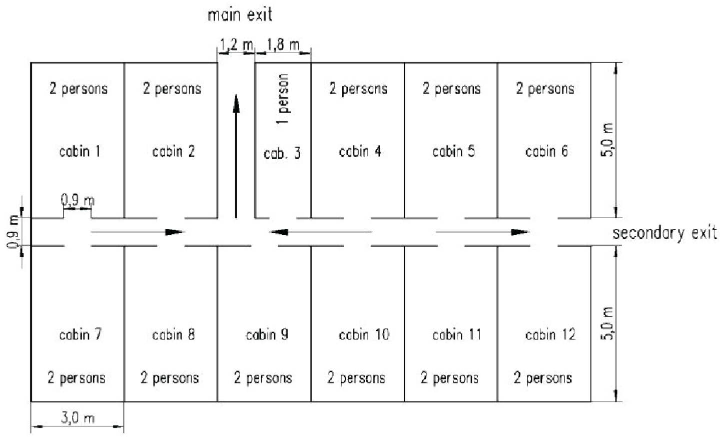


Figure: Appen. D. 37: Background image from IMO

This image (IMO, 2016) used in the Pathfinder model as the background image for the design.

As per the given guidelines in IMO, 23 occupants in the age group 30 – 50 years, without initial delay were randomly allocated in cabins. The occupants (blue) in cabins 1, 2, 3, 4, 7, 8, 9 and 10 were assigned the main exit while all others (cabin 5, 6, 11 and 12 in orange) were assigned the secondary exit.

Table 3.4 – Walking speed on flat terrain (e.g. corridors)

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

Figure: Appen. D. 38: Table 3.4 from IMO

(IMO, 2016)

The walking speed characteristics were

The result expected was that all occupants exit using the exits assigned to them.

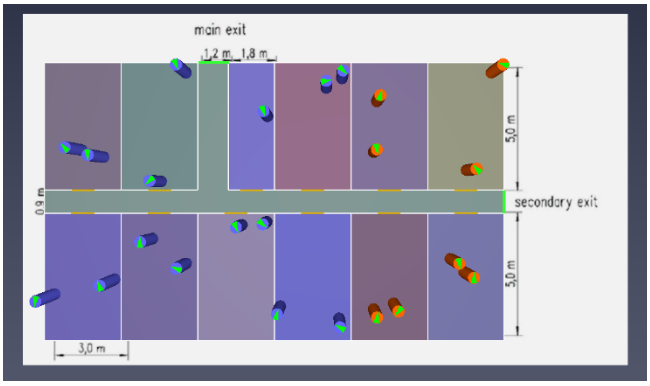


Figure: Appen. D. 39: View of modelling GUI at the end of modelling.

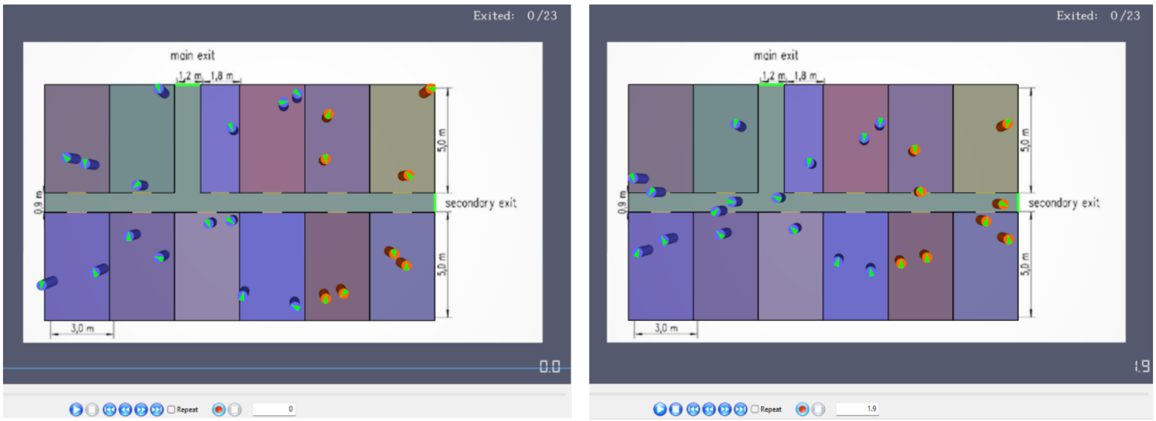


Figure: Appen. D. 40: View of model and simulation GUI at initial positions

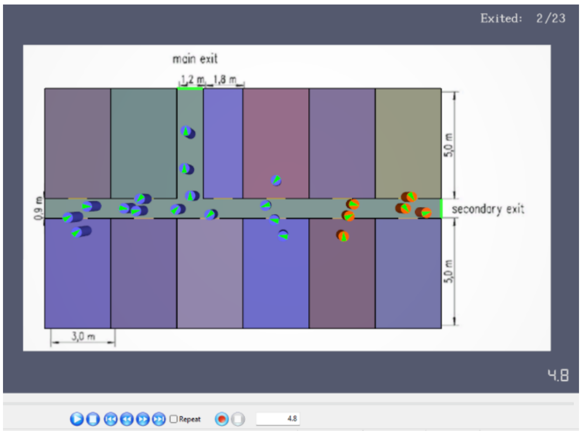


Figure: Appen. D. 41

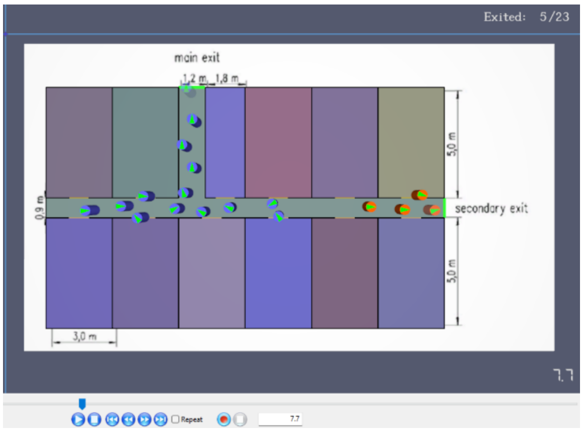


Figure: Appen. D: 42

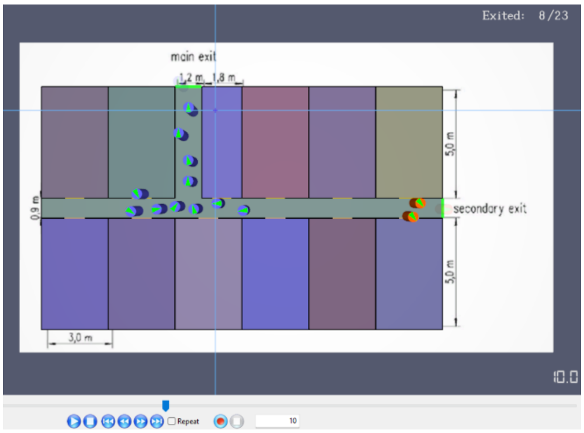


Figure: Appen. D. 43

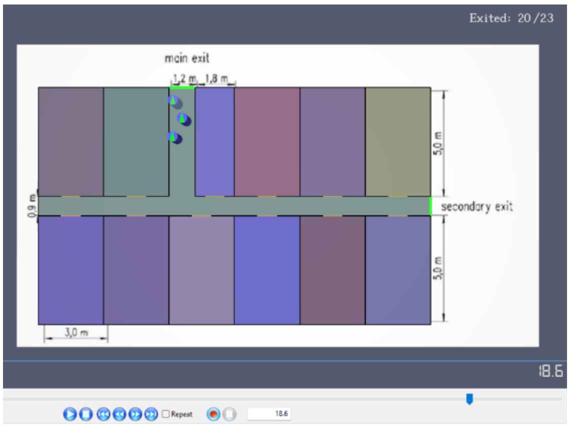


Figure: Appen. D. 42

By referring the figures Appen. D. 39 to 44, it can be seen that both blue and orange occupants move only towards their assigned exits. So, verification can confirm that Pathfinder performs as expected in this test.

Appendix E

Since there are only 2 dimensions specified in the image (48 m in X direction and 12 m in Y direction), the longest specification 48 m (X direction) was the best choice for the scale to minimize the scaling error on the PF model. Once 48 m X direction was chosen to specify the scale, then, when checked the length of Y direction at the point specified as 12 m, it was found that the coordination in PF model does not show as 12 m. This mismatch indicates that the scales in X and Y directions differ to each other.

This mismatch demanded the development of another supportive additional model to find out essential measurements in Y direction. (This model was developed using 12 m - Y directional measurement indicator as the scale developer to this model). Likewise, all Y directional measurements (as an example the length of a cabin) were found, still with very closer approximation on necessary positions and thereby reading the coordination shows in PF model. **(This method of finding the necessary dimensions by reading the coordination with mouse-curser positioning can inherently be involved with human errors)**

There are 12 cabins located along 48 m as shown in the sketch. So, width of one room could easily be calculated as 4 m. The cabin length was a very close approximation found by the other supportive PF model (PF model name: AppenB Support) as explained in the above paragraph and found as 4.8 m.

Then, the width of the corridor was found through a calculation, 12 – (4.8 x 2 rooms) = 2.4 m.

The 2 exit doors of dormitory, each with 2 m width as mentioned in (Lei, et al., 2012), but still lacking the specific dimensional information for the relative placement within the building. So, this is located as best as possible using the background image in the PF model.

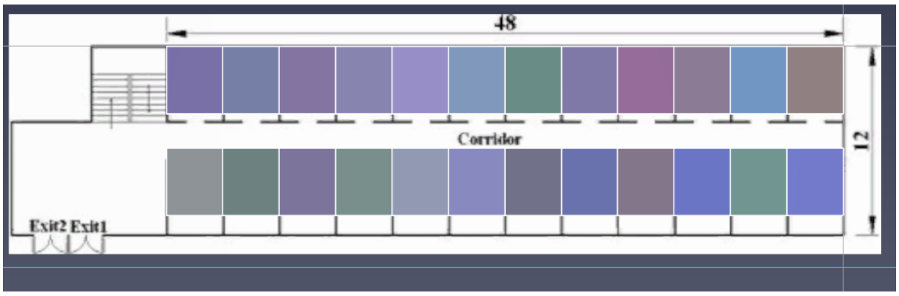


Figure: Appen. E. 1: View at the end of modelling 24 rooms.

This plan view picture of PF model clearly shows the mismatch of Y direction, but in the X direction, cabins in PF is very closely coincide with the cabins in the background image.

Appendix F

Following are some examples that Pathfinder has given provision to simulate the effects of hazardous conditions in its simulations.

- There is a parameter – Speed in Smoke – under the advance tab of edit profile dialog box of occupants which enable the occupant's speed variation under smoke.
- In PF for example, user can decide on whether an obstacle would be displayed in Results or not. This might be useful, for instance, if the obstacle is being used to re-route occupants due to an environmental hazard such as smoke or fire (Thunderhead Engineering, 2024).
- In the use of elevators in PF, there is a parameter within Elevator Properties – Floor Priority - that is used to prioritise a floor which gets the elevator service first, which might be useful in prioritising any floor that met with an emergency.
- There is a parameter in Room Properties panel - Speed Modifier - that affects on the speed of the occupants using the respective room, which might be used, for instance, to represent the effect of smoke on occupants.
- In the simulation result output CSV file named "Occupant Parameters CSV file", there is a data column speedInSmoke (m/s) under which presents the occupant's reaction to Smoke when running an FDS coupled simulation.