A Modelling Study on the Impact of Luggage and Airworthiness Certification on Aircraft Evacuation

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En modelleringsstudie över påverkan av bagage och flygduglighets certifikation för flygplansutrymning.

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Abstract

Real-life aircraft evacuation drills can cost up to 2 million USD and may not at the same time be able to represent a real emergency scenario. with the use of evacuation models as a complement to the testing may reduce this cost. The aim of this thesis is to test the capabilities and limitation of two continuous evacuation models, namely Pathfinder and FDS + Evac in representing aircraft evacuation scenarios. The simulations were conducted considering six different scenarios which included 90s certification scenario and rapid deplaning with and without luggage and were simulated in an Airbus A320. The simulation work highlights the required user calibration effort to consider the narrow spaces in aircraft evacuation modelling scenarios. It also concludes that evacuation models allow the quantification of the impact of luggage on an increased total evacuation time by almost 8 % for Pathfinder and 2.5 % for FDS+Evac. The work highlighted the limitations both models possess in representing the narrow geometry of an Aircraft due to the use of 2D space representation and the use of rigid bodies. However, models such as Pathfinder allow behavioural itineraries which is more suitable for representing luggage collection.

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Summary

Aircraft evacuation differs from the conventional evacuation of buildings. The narrow geometry challenges the evacuation and with further obstacles such as luggage challenges it even more. To certify an aircraft for airworthiness, tests of the evacuation capabilities of an aircraft must be done and achieved under 90 seconds. This is a testing that can cost up to 2 million dollars and at the same time may not reflect the real conditions of an emergency. By using evacuation modelling it is possible to consider multiple scenarios, i.e., it is possible to simulate scenarios with and without luggage.

The aim of this thesis was to test the capabilities and highlight limitations in aircraft evacuation modelling scenarios for continuous evacuation models. Two software have been used for this purpose, namely i.e., Pathfinder and FDS+Evac. The scenarios of 90 second certification and rapid deplaning with real testing from a small-scale trial has been used. The simulation was done in an Airbus A320 which is one of the most used commercial aircraft as for today.

A literature study over current evacuation modelling software specifically designed for aircraft evacuation scenarios has been done to review their capabilities and purposes. The main use of evacuation modelling tools is generally certification purposes, to be a complement to the real-life tests to reduce costs of the testing. The review included three models; airEXODUS, VacateAir and ETSIA where their purpose was mainly associated with certification.

To understand human behaviour during an aircraft evacuation and calibrate models for the case study, data has been compiled from publicly available video recordings of evacuation scenarios that one of the passengers had filmed. The conclusion from the videos was that a large number of passengers tend to bring their luggage with them despite the crew telling them not to. The luggage they bring range from small purses to the bigger carry-on luggage.

A data-set from the National Research Council of Canada focusing on investigating micro-behaviours during an aircraft evacuation has been used to calibrate a set of simulations. The results show that both Pathfinder and FDS+Evac are able to represent (implicitly or explicitly) the key behaviour in aircraft evacuation scenarios. Both models require a user effort in the calibration phase given issues in modelling narrow spaces (i.e. space between the seats), with FDS+Evac seeming to be more sensitive to this issue. The scenarios with the luggage give an increase of almost 8 % for Pathfinder and 2.5 % for FDS+Evac. The representation of the impact of luggage can be done in current models implicitly, i.e. representing an additional delay during the evacuation process. Nevertheless, models allow different approaches for this representation, with the way-point function available in Pathfinder being useful to represent this behaviour more accurately. Using the given input configuration, the results also show that FDS+Evac is more sensitive to changes or randomizations of inputs.

Both models also make use of 2D representation of the space which do not explicitly represent the low height above the seats and above the overwing exits of an Aircraft. This would result in increase in total time for evacuation throughout all of the scenarios. The models also use rigid bodies which means that the occupants are not able to squeeze in between other occupants and the narrow space of the aircraft.

Sammanfattning

Flygplansevakuering skiljer sig från den konventionella evakueringen av byggnader. Den smala geometrin utmanar evakueringen och utmanar det ytterligare med hinder som exempelvis bagage. För att certifiera ett flygplan för flygduglighet testas evakueringsförmågan hos ett flygplan och måste uppnås under 90 sekunder. Detta är ett test som kan kosta upp till 2 miljoner dollar och samtidigt reflekterar inte på de riktiga förutsättningarna i en nödsituation. Genom att använda evakueringsmodellering kan kostnaderna reduceras och det svåra förutsättningarna av en verklig nödsituation kan simuleras med och utan bagage.

Målet med denna avhandling var att testa kapaciteten och upptäcka begränsningar för flygplansmodellering i evakueringsmodellerna Pathfinder och FDS + Evac. Scenarierna för 90 sekunders certifiering och snabb planering med data från ett småskaligt försök. Simuleringen gjordes i en Airbus A320 som är idag ett av de mest använda kommersiella flygplanen.

En litteraturstudie om nuvarande evakueringsmodeller har gjorts för att se över deras kapacitet och syften. Det huvudsakliga syftet varför flygplansevakueringsmodellering finns är för certifieringsändamål, för att komplettera de verkliga testen och för att minska kostnaderna för testerna. Studien genomfördes över tre modeller; airEXODUS, VacateAir och ETSIA där deras syftet var främst för certifiering.

För att förstå det mänskliga beteendet över en flygplan evakuering har en studie gjorts genom att granska videoinspelningar över en evakuering som en av passagerarna hade filmat. Slutsatsen från videon var att ett stort antal passagerare tog med sig sitt bagage trots att besättningen säger att de inte ska. Bagaget de tar är allt från handväskor till större bagage.

Data fokuserad på mikrobeteenden under flygplansutrymning från National Research Council of Canada användes som indata i några av scenarierna. Resultaten visa på att både Pathfinder och FDS+Evac kan presentera de huvudsakliga beteendena under flygplansutrymning. Båda modellerna är beroende av användaren under kalibreringsfasen givet de problem som modellerna har med trånga utrymmen (med andra ord mellan sätena) vilket FDS+Evac visar sig vara mer känslig till. Scenarierna med bagage visar på en ökning på nästan 8 % för Pathfinder och 2.5 % för FDS+Evac. Representationen bagens påverkan kan implicit utföras i modellerna, med andra ord använda sig av en extra fördröjning under utrymningsprocessen. Modellerna tillåter olika sätt för den representationen, med den användbara way-point funktionen som Pathfinder har tillgång till för att bäst representera detta beteende. FDS+Evac visar samtidigt på en större känslighet för slumpmässiga ändringar på den givna indatan.

Båda modeller använder sig av 2D representation av utrymmet vilket inte representera verkligheten med den låga höjden mellan tak och golv mellan sätena och vid utgångarna vid vingarna i ett flygplan. Detta skulle innebära en ökning av den totala tiden för utrymning för samtliga scenarier. Modellerna använder sig även av fasta kroppar, det vill säga att kropparna inte kan pressa sig fram mellan andra kroppar och det trånga utrymmet i ett flygplan.

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1 Introduction

Evacuation of airplanes differs considerably from more conventional evacuation in buildings. Several people in a limited amount of space can greatly challenge the evacuation capacity. Prior accidents involving evacuation from a commercial airplane include a Boeing 737 (USAir) on 1 February 1991 (National transportation safety board, 1991) which collided on the runway with another plane. All of the passengers on the other plane died on impact but none of the passengers on the 737 died on impact but 19 died due to smoke in the cabin. The problem here was queue in one of the exits. Another example is on 19 November 1996 another collision occurred whereas no one died on impact but due to smoke filling the cabin (National transportation safety board, 1997). In this case the problem was that the pilots were unable to open the forward air stair door. The type of plane in the last example was a Beechcraft 1900C which is a small plane with only one exit. In Table 1 below further accidents between 2010-2018 which contained evacuation from the aircraft is listed (Butcher, Barnett, Buckland, & Weeks, 2018).

Table 1. Accidents between 2010-2018 involving emergency evacuation of the Aircraft

Date:	Location:	Aeroplane Type:	Number of passengers and crew onboard	Number of Passenger and Crew fatalities
04/11/2010	Singapore	Airbus A380	Passengers: 440. Crew: 29.	Passengers: 0 Crew: 0
16/04/2012	London Gatwick, UK.	Airbus A330-300	Passengers: 304. Crew: 13.	Passengers: 0 Crew: 0
22/12/2012	Nunavut, Canada	Fairchild SA227-AC Metro III	Passengers: 7. Crew: 2.	Passengers: 1 Crew: 0
06/07/2013	San Francisco, USA	Boeing 777-2000	Passengers: 291. Crew: 16	Passengers: 3 Crew: 0
29/03/2015	Halifax, Canada	Airbus A320-200	Passengers: 133. Crew: 5.	Passengers: 0 Crew: 0
08/09/2015	Las Vegas, USA	Boeing 777-200	Passengers: 157. Crew: 13.	Passengers: 0 Crew: 0
27/05/2016	Tokyo, Japan	Boeing 777-300	Passengers: 302. Crew: 17.	Passengers: 0 Crew: 0
26/06/2016	London Heathrow, UK	Airbus A330-300	Passengers: 277 Crew: 12	Passengers: 0 Crew: 0
27/06/2016	Singapore	Boeing 777-300	Passengers: 222. Crew: 19.	Passengers: 0 Crew: 0
03/08/2016	Dubai, United Arab Emirates	Boeing 777-300	Passengers: 282. Crew: 18.	Passengers: 0 Crew: 0

13/01/2018	Trabzon, Turkey	Boeing 737-800	Passengers: 162 Crew: 6.	Passengers: 0 Crew: 0

Disembarking an aircraft is typically conducted under one of several scenarios, for example: ordered deplaning, rapid deplaning, 90s deplaning and an emergency evacuation. Ordered deplaning is the normal, everyday disembarking of an aircraft as part of routine operations. 90s deplaning is a trial conducted in real life for an aircraft model before it is put in to commercial use. The objective with the 90s deplaning trial is to evacuate an entire aircraft in less than 90 seconds. The trial will be discussed in more detail in section 3.

Rapid deplaning is conducted in response to an emergency scenario onboard the aircraft whilst the aircraft is still standing at the gate, either still connected to the airport by a passenger-loading bridge or by boarding steps (Flight Safety Foundation, 2002). The reason why evacuation is only done by the door connected to the airport by airbridge is due to the known likelihood of injuries when using overwing exits and slides.

Depending on the airplane’s configuration of the cabin, the evacuation time can vary significantly. Changes in configuration in conjunction with passenger behaviour can affect individual movement and therefore overall evacuation time. The National Research Council of Canada (NRCC) has found this conclusion through a series of tests (Gwynne, o.a., 2017). In their tests they changed the seat pitch to see that when increasing the seat pitch the movement time between the seats decreased. These tests were made with predefined but commonly used microbehaviours and with these behaviours there is a lot of influential factors that could influence how the people move through the cabin and seat rows. With evacuation modelling programs these microbehaviours and their influential factors can be implemented where one could vary the inputs far more than one could during a real test.

The usage of evacuation modelling gives the opportunity to save time and reduce costs for the aircraft manufactures. In fact, one of the main issues of having evacuation drills, with real people, is the costs as it can go as high as 2,3 million US dollar (Xue & Bloebaum, 2008) while costs for using a simulation tool is considerably less. Another issue with using real people is the risks of the trial itself meaning that there is a risk for injuries. For example, during an evacuation trial for a McDonnell Douglas MD-11 aircraft in October 1991 a female volunteer sustained severe injuries leading to permanent paralysis (Galea, Owen, & Lawrence, 1996). An evacuation model would perhaps not replace the trials with real humans but would serve as a great complement in collecting data for the trial.

The main problem from a scientific point of view is that conducting evacuation drills with people and eliminating the risks for injuries, stress or trauma during the trials, can lead to decrease the validity of such scenarios. A real emergency situation may sometimes contain smoke and fire which cannot be included in a large-scale trial given the risks of the volunteers, which could be represented in fire evacuation simulations. In real evacuation another issue which real-life tests do not take into account is the collecting of luggage people do during an evacuation. This is a factor that evacuation modelling tool may be able to reproduce such scenario.

1.1 Objectives

This thesis reviews the capabilities and limitations of evacuation models for a selected set of aircraft evacuation scenarios adopting different modelling methods. The different methods in this thesis consists of a continuous model based on steering movement approach (Reynolds, 1999) and a continuous model based on force-based movement (Helbing & Molnar, 1995). The models will be configured to reflect recent experimental work to assess the impact of the presence / absence of luggage on deplaning scenarios and the capability to be used for certification, design and accident reconstruction.

2 Methodology

The thesis will consist of a literature study in which firstly the current regulations for airworthiness will be reviewed in both the US and Europe. Secondly current research done in the field of aircraft evacuation will be reviewed. After the literature study two simulation models, Pathfinder (Thunderhead Engineering, 2018) and FDS + Evac (Korhonen, 2018), will be tested with the following scenarios:

- Rapid deplaning
    - 50 % of passengers bring luggage
    - None of passengers bring luggage
- 90s deplaning
    - None of passengers bring luggage

90s deplaning is a required scenario for the aircraft to receive its certification of airworthiness (Federal Aviation Administration, 2015). The scenario states that the entire aircraft is to be able to be evacuated in less than 90 seconds through half of the available exits.

During rapid deplaning only one exit is available as the aircraft is still connected to the airport by a passenger-loading bridge/jetbridge and slides cannot be deployed. In this scenario it is also highly likely that the passenger will collect their luggage compared to the 90s scenario where there are no luggage present according to the regulations. There are no available data on how long a rapid deplaning lasts, but it is safe to assume that it is over 90 seconds. In this case it is not relevant to know the evacuation time for rapid deplaning rather the difference in evacuation time between the trials.

The simulations of the rapid deplaning scenario will be using data collected from small scale trials, see section 7, instead of using the data provided in the simulation model to create a more realistic results given the unusual environment of evacuation. The 90s deplaning scenario will use the data provided in the model regarding walking speeds and the distribution of passengers give in the regulations. The scenarios will be simulated in an Airbus A320 which is currently the most used commercial aircraft in the world (The Guardian, 2012).

The following inputs that will be needed and used in the simulations are:

- The time it takes to leave the seats.
- The time it takes to collect luggage from overhead bins.
- Aircraft dimensions.
- The size of agents used in FDS + Evac and Pathfinder to adjust the distance between the seats in the aircraft.
- Pedestrian walking speeds.
- Certification inputs related to the 90s deplaning scenario.

The inputs are presented in detail in section 6.

As evacuation models use a stochastic approach and pseudo-random sampling from distributions, the simulations will be repeated to studying convergence of results and aiming at a behavioural uncertainty below 2 % (Ronchi, Reneke, & Peacock, 2014).

2.1 Pathfinder

Pathfinder is a continuous model which uses two ways to model evacuation movement. One model uses the SFPE method in calculating the flow (SFPE, 2003). The other model is an agent-based model, based on a steering modelling approach (Reynolds, 1999), which takes to account queuing and congestion. Pathfinder does the calculation for each individual agent such as the shortest path to the exit and the interaction with the environment and other agents.

The user can by her/himself implement a large amount of inputs such as walking speed, delay times, body size, comfort distance, etc. Almost all of the inputs can be assigned by distribution laws, from which the model will sample values using pseudo-random sampling. The agents follow three rules along the egress path; avoid other occupants, avoid walls and seek after exits.

Pathfinder allows the user to for each individual assign delay time, which doors it should choose, waypoints, wait time and wait for assistance. All of these inputs can be combined in many different ways which gives a lot of opportunity to customize the behaviours in the agents.

2.2 FDS + Evac

FDS + Evac is a continuous evacuation model which is implemented in FDS. The model is integrated with CFD which allows the agents to interact with the changes of conditions during an evacuation, for example smoke development. Like in Pathfinder each occupant has their own set of characteristics. The main characteristics of people are represented by two stochastic variables: response time and walking speed, with a set of five default categories of agents. The five different types of agents that can be chosen is; Male, Female, Adult, Child and Elderly. The agents are represented by three ellipses, one for the body and two for the arms and has a body size distribution built in.

When choosing doors, the agents in FDS + Evac generally choose the exit depending on where the other agents go. This is a part of the sub model which controls the group behaviour (Korhonen, 2018). Various factors can be taken into consideration to alter the choice of exit beside the social behaviour (e.g. familiarity, presence of smoke, toxicity, etc.). The user can choose which doors the agents are familiar with and will go to and what the probability of them doing so is.

2.3 Airbus A320

The Airbus A320 is the most used commercial aircraft in the world with over 4000 A320s operating worldwide (The Guardian, 2012). The A320 has a length of 37,57 meters and a typical configuration of 165 seats. The aircraft consists of a single aisle seating with three seats in a row (Airbus, u.d.).

2.4 Delimitations

This thesis will only focus on two commercially used continuous evacuation modelling tools, namely Pathfinder and FDS+Evac. The simulations will be done in one of the most common commercial aircraft, the Airbus A320 (The Guardian, 2012). The study will focus on six different scenarios in which the walking speeds, social force/comfort distance, size of the aisle, the body sizes of the agents and pre-evacuation time will be subject to change. This thesis will not consider people with any kind of disabilities in the simulations. In the small-scale trial the participants were provided with light packed luggage which do not reflect with the often heavy luggage in reality.

3 Aircraft evacuation legislation

The configuration of an airplane is regulated by the flight agencies of the countries or union the aircraft manufacture company belongs to. These regulations can be for example the width between seats and the required time for evacuation. In this chapter the regulations for the two largest parts of the world in air traffic will be reviewed.

3.1 Aircraft regulation agencies

In the United States the FAA (Federal aviation agency) is the controlling body of the air traffic. The United States government sets the regulation and the FAA implements them.

The EASA (European Aviations Safety) is the controlling body of the air traffic and airplane safety in the EU and is the head department for all of the EU members agencies.

3.2 Aircraft evacuation regulations

To achieve the certification of airworthiness the aircraft must meet the designs standards of the aviation agency in concerned country and the aircraft must be safe to operate (Federal Aviation Administration, 2015). One aspect of designing a plane correctly is making sure that evacuation procedures can be executed fast and safe. The regulations states that under simulated conditions an airplane and its crew must be designed and organized to be able to evacuate the entire aircraft in 90 seconds with half of the exist blocked. This 90s rule is only a requirement for aircrafts that can carry over 44 passengers (European Aviation Safety Agency, 2012). To pass the trail and get the certification the trial only needs to be passed only once.

The trials are to be done by night to test out the aircraft emergency lightning. The volunteers participating in the trial are of a specific mix where at least 30 percent must be female and at least 5 percent of the total amount of volunteers must be over 60 years old. It is also required that at least three of the passengers carries a real-life sized child of 2 years or younger. This means that there is no requirement to have children over 2 years old, people with disabilities and intoxicated passengers which is a more likely scenario to have onboard an aircraft.

To achieve a 90 second evacuation the cabin crew need to be in sufficient numbers and organized in a way to handle a lot of passengers in a small area. The EASA uses a common rule in the Aircraft Agency community in this case and it is the “One-per-50” rule. The rule states that in every 50 passengers there should be one crew to take care of them during an evacuation. But it is not a rule that is always required. In larger airplane the cabin crew members could be lower than if implemented the “One-per-50” rule. In that case a risk assessment must have been made and an evaluation on the tasks and routines the cabin crew are to have.

With the number of seats, the size of the doors in an aircraft varies. For example, the largest door (Type A) can increase the number of seats allowed on the aircraft up to 110, given door placement on both sides of the fuselage. The doors used by the passengers should be designed for everybody to open which means simple and obvious. The door should also be designed so it takes less than 10s from closed to fully opened position. For the type A door, the passageway leading to the door must be at least 91 cm wide. The other doors should have a passageway with a minimum width of 51 cm. In Table 2 below the different types of updated exits is shown (Hedo & Martinez-Val, 2011).

Table 2. Dimensions and evacuation capacity of exit types

	Minimum dimensions		Seating capacity
Exit type	Width, m	Height, m	(no. passengers)
A	1.07	1.83	110
B	0.81	1.83	75
C	0.76	1.22	55
I	0.61	1.22	45
III	0.51	0.91	35

The passageway to type A exit must be at least 91 cm wide and for all other doors it must be at least 51 cm. Each passageway must have adequate space to allow crew members to assist during passengers during the evacuation. For type A exits there must be space on both sides of the passageway for the crew members and for the all other doors only one side of the passageway must have space for crew members.

4 Current evacuation modelling studies

Given their potential, there is a great need to assess the capabilities of evacuation models for aircraft scenarios. There is a set of models today specifically developed for aircraft evacuation modelling, for instance airEXODUS (Galea, Blake, & Lawrence, 2005), VacateAir (Galea, Owen, & Lawrence, 1996), and CabinEvacu (Hong-bing, Xiao-fang, Xin, & Zhen-yu, 2018).

Aircraft evacuation simulation follows about the same principles in evacuation simulations as shown in below Figure 1 and are the deciding factors in the total evacuation time.

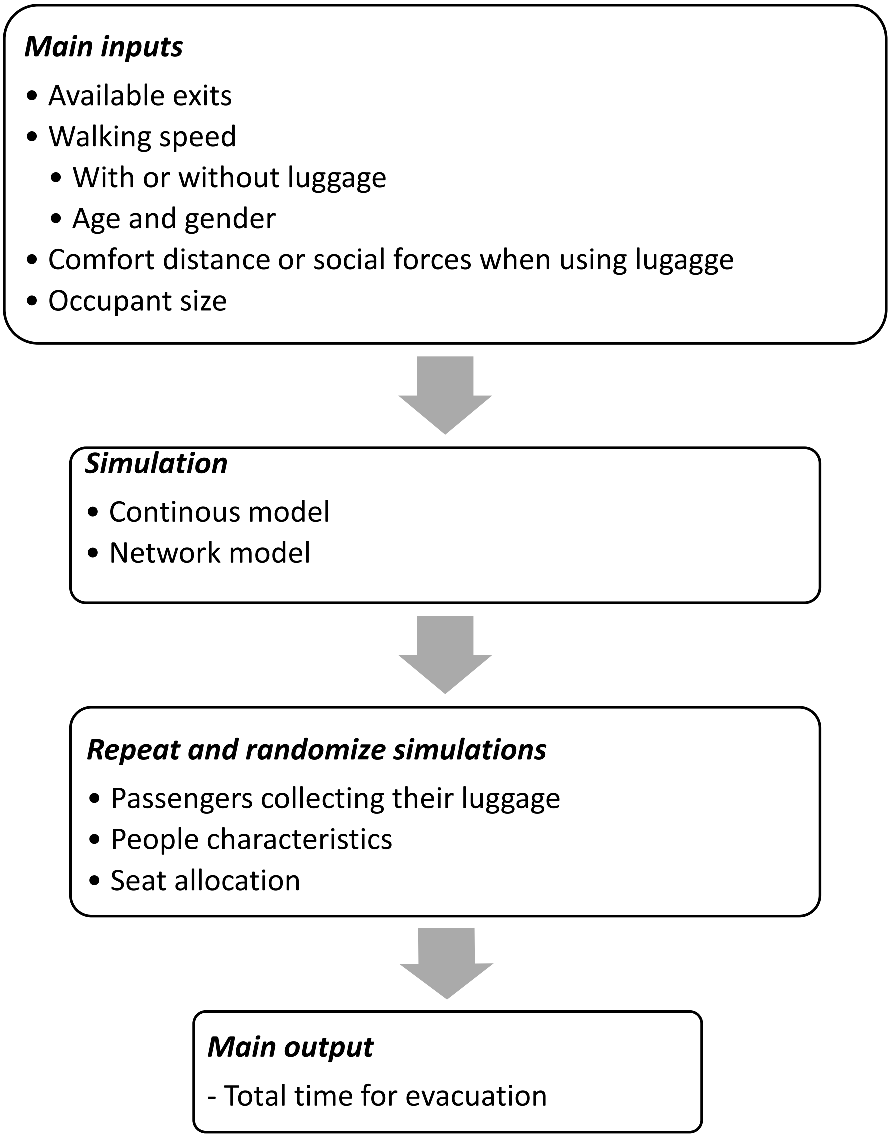

Figure 1. Flowchart of evacuation simulation

The research that has been done in most of the evacuation models is based on the 90s trial which means that the scenarios used is predefined by regulations put out by FAA and EASA, as mentioned in the previous section 3.2.

In this section of the thesis the current research done in this field will be reviewed for VacateAir, airEXODUS and ETSIA. These are programs designed specific for aircraft evacuation modelling.

4.1 airEXODUS

The simulation program EXODUS is a two-dimensional grid-based model. The model contains five interacting sub models, the occupant, movement, behaviour, toxicity and hazard sub models. The behaviour of each individual and progressive motion is being determined by a set of rules or heuristics (University of Greenwich, 2003).

The base program EXODUS in which airEXODUS is based from the model had the following defining attributes to be used in aircraft modelling (Galea, Blake, & Lawrence, 2005);

- Name (seat location)
- Gender
- Age
- Weight
- Condition
- Mobility
- Patience
- Agility
- Travelspeed
- Volume of air breathed (RMV)
- Incapacitation dose (D)
- Response time
- Drive

Some of the attributes are fixed while others change as they are inputs from the other sub-models.

The model has been compared with experimental data from aircraft evacuation trials which was under competitive and non-hazard conditions. The model was able to correctly predict observed experimental trends. Results shows that airEXODUS predicts the total evacuation time with an accuracy of 5.3 % when using actual data from previous trials. The simulations were done in several different types of aircraft, both narrow and wide spaced. The models are also shown to predict the evolution of the evacuation from start to end (Galea, Blake, & Lawrence, 2005).

These results are all based on the 90s trials with strict pre-defined conditions and relies on test-data for the scenarios used. For example, if a type A door is used in the simulation, data from a type A door needs to be used, data from a series of rigorous testing. When new components are introduced new data needs to be provided to be able to further simulate the evacuation.

4.2 ETSIA

ETSIA, Evacuation Test Simulation and Investigation Algorithm, is an agent-based computer model (Hedo & Martinez-Val, 2011). It was designed for handling the 90s certification scenarios. The model is currently designed for the most common type of aircraft body; the narrow body aircraft. For example, the Airbus A320 is a narrow body aircraft.

The model consists of three sub-models: time, geometry and occupants. The geometry sub-model handles elements such as seats, exits, deployable slides, aisles, etc. The seats for the passengers require detailed information due to its great diversity of arrangements. The sub-model divides the information into two classes: zone and block. A block is a set of joint seats and a zone is a set of blocks. A zone consist of 11 different attributes: the number of seats per block, the coordinates of the block, the seat width, the armrest width, the width between blocks (longitudinal), the seat depth, (if it exist the lateral width between blocks), a flag digit to mark the existence of an aisle on the left, and one flag to the right aisle. The occupants in the model move continuous but to be able to handle such movement the model converts the floor area into grids.

The occupants on the aircraft are either passengers or crew members and only gender and age has been considered when modelling which is according to the regulations. Age is divided into junior and senior where junior is less or equal to 49 years. The distribution of age and gender are already predefined from the airworthiness regulations as discussed in 3.2 but the passengers are randomly seated across the aircraft. All of the crew member however is considered to be in good physical conditions therefore age will not have an effect on the crew as it will have on the passengers. Depending on the age of the passengers they will have different type of movement speed which follows a normal distribution.

The third sub-model, time, marks the rhythm a performance of the simulation. The end-goal for the sub-model is to check if the total time for evacuation is less than 90s, $T_{eva} = t_{end} - t_{sta} < 90$.

Each occupant has three attributes assigned to them except gender and age: reaction time, kinematic factor and exit hesitation time. The reaction time is randomly determined by a Weibull distribution, the kinematic factor is Gaussian and dependent on age and gender and exit hesitation time is generated by a Poisson distribution.

The selection of exits by the occupants is done by using parametric sweeping which improves uniformity among exit occupancy. This simulates the behaviour of the occupants well and optimizes the evacuation process which is the case in the 90s trials. Simulating the movement speed from pneumatic slides can be difficult to simulate but in this model the problem was solved by combining horizontal and vertical speed.

The model has been tested against stability against random variation of the intervening variables and stability against input data errors (Hedo & Martinez-Val, 2011). Input data errors can be for example a slight distance error, in this case an input data shift of 10 cm (the doors were shifted 10 cm in various directions) was implemented and the model showed a very small difference in the results.

Overall results show that the model handles 90s rule scenarios very well and in all the simulations done in this research one in 1000 simulations gave a result higher than 90s. The model also shows great potential in evacuation design having great impact in changing exit types and allows overall better understanding of the evacuation process.

4.3 VacateAir

VacateAir (Xue & Bloebaum, 2008) was designed to simulate both a non-emergency scenario such as the 90s trial and emergency scenarios. The model is a modification of the base model *Vacate* which is a simulation model designed for building evacuation. VacateAir is a Particle Swarm Optimization (PSO) model with based stochastic evacuation in where each human is represented by a particle with their own velocity.

PSO is a simple method originally based on birds flocking. Just like birds, humans want to keep a distance between on another while moving towards an optimal location (exit in an evacuation scenario).

VacateAir consist of four sub-models: the Cabin Configuration System (CCS), the Fire Hazard Model in Aircraft Evacuation (FHMAE), the Human Behaviour System in Aircraft Evacuation (HBSAE) and the Behaviour Simulation System in Aircraft Evacuation (BSSAE). CCS controls the passenger's seat assignment and changes the environment of the cabin depending on the hazard's location i.e. which exit is available and obstacles. FHMAE uses data from Fire Dynamics Simulator (National Institute of Standards and Technology, u.d.) which consists of soot density, temperatures, toxic gases and visibility. HBSAE is used to predict the pre-evacuation time, exit selection of crew and passengers, passenger moving speed and individual behaviour. BSSAE uses the outputs from HBSAE and predicts the movement behaviour of the passengers which can be put in two ways: cooperative behaviour and competitive behaviour. As the name suggest cooperative behaviour is a polite type of movement where people are waiting in turn to move and exit. This gives however longer waiting distance between the seat row and aisle and a lower density in the aisle. The competitive behaviour has a more aggressive movement from the passenger with a higher tendency to move in a group in which the passengers has social ties with.

Results shows that VacateAir predictions compare well evacuation time quite accurately when compared to real test data with different types of combinations of human behaviour and cabin configurations. The more extreme cases of human behaviour could not be validated due to the limitations of trials with real people which limits the model to usage of only certification evacuation and not a scenario based evacuation.

4.4 Capabilities and limitations of the models

The common feature with the models of ETSIA, airEXODUS and VacateAir is that they are all primarily designed for 90s certification use. Their main validation tests come from trials done with 90s scenario with real people. ETSIA has also a purpose to be able to help with the design of new aircraft cabins in terms of evacuation and AirEXODUS also has a purpose for accident reconstruction.

Both VacateAir and ETSIA are continuous models whereas airEXODUS is a grid-based model. The disadvantage a grid-based model has is that the movement is depending on the size of the grids used. But with a continuous model the movement gets a more natural flow. With a grid model it can be difficult to choose the grid and model a manageable geometry for the occupants.

When modelling human behaviour ETSIA and VacateAir works similar with both of the models considering both the individual behaviours and the behaviours implied by humans when moving as a group. airEXODUS does not model group behaviour such as family bonds. airEXODUS also does not model behaviour involving disability which may affect the evacuation process. ETSIA does not show if it does consider disability when modelling human behaviour whereas in VacateAir it is part of one of the sub-models.

5 Aircraft evacuation behaviour in a real emergency

In evacuation scenarios from buildings human behaviour can differ from evacuations scenarios from an aircraft for the people involved. The space in an aircraft is very limited and gets easily crowded in a very short amount of time. In Figure 2 below the general evacuation process in real emergency situations from an Aircraft is shown.

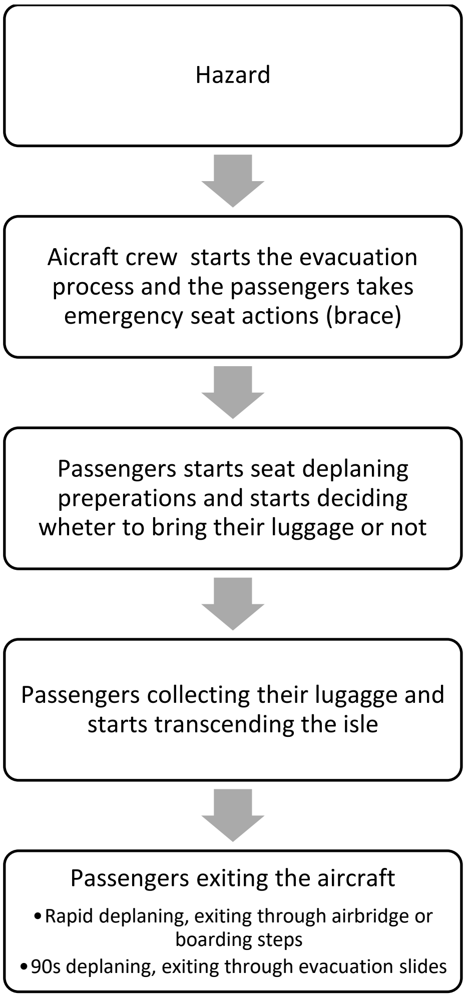

Figure 2. Aircraft evacuation flowchart

The first step in an evacuation is the crew members announcing the passengers to prepare for evacuation. In an emergency landing scenario, the passengers are first asked to brace. The passengers are then told to leave all their belongings behind and to not use their cellphones.

Although instructed otherwise, some of the passengers might begin their evacuation by collecting their personal belongings either under the seats or in the over-head locker. After collecting their personal belongings, they will begin to move to the exits. What determines the passengers' movement speed are: people collecting their luggage, obstructions such as luggage on the floor, crew members, slow moving passengers due to congestion and/or age.

5.1 Case study Dynamic Airways Flight 405

An example of the issues associated with carrying luggage during an evacuation, is the case of Dynamic Airways 405 evacuation on October 29, 2015 in Fort Lauderdale – Hollywood International Airport, Florida. This was reviewed to determine different types of behaviour that can be observed during an aircraft evacuation. This video was shot outside of the aircraft and does not therefore show the evacuation from the inside. Despite this issue, the video provides valuable information about passengers handling their hand luggage (Gpluz, 2015).

The largest problem that was seen on the video of the emergency evacuation of flight 405 was that a large number of passengers did collect their luggage, which can be seen in Figure 3, despite the cabin crew telling them not to as a standard procedure. The passengers may have an economically or emotionally tie to the hand luggage and do not want to leave it at any cost, i.e property attachment. If you have for an example a passport or an expensive computer with family photos saved from the trip you just did, the chance of you leaving that hand luggage behind is quite small.

These types of behaviour root into the issue that passengers do not listen, pay attention to, or comply with the cabin crew instructions on not collecting the hand luggage or using the cellphones. In an emergency people may not understand to which extent a behaviour could damage others during an evacuation. People may not think that by collecting hand luggage which only takes a few seconds may end up blocking other passengers when combing all the passengers that hold their hand luggage. These small moments can indeed add up to a large number of seconds.

Figure 3. The evacuation of Dynamic Airlines Flight 405 (Shapiro & Tienabeso, 2015)

5.2 Case study American Airlines flight 383

A second case study has been reviewed, the American Airlines Flight 383 evacuation on October 28, 2016 in Chicago O'Hare International Airport; it has been studied to determine the use of different type of behaviour during an aircraft evacuation. This is one of the few recorded real evacuation scenarios due to the restricted use of cellphones during an evacuation (Cardenas, 2016).

On the 28 of October 2016 a fire broke out in the right engine of Flight 383. The crew managed to abort the flight and stopped on the runway. The evacuation of the aircraft could then begin and everyone onboard managed to evacuate.

In this case the evacuation of flight 383 took almost 6,5 minutes (Greenberg, 2016). That is far off from the 90 seconds the FAA wants and that is mainly due to the human behaviours and not the design or technical aspects of the aircraft. The evacuation of flight 405 took significantly lower time than the flight 383, it is not stated in any report about how long the evacuation took, however, the video indicates that the evacuation took less than 3 minutes (but longer than 90s).

With the new technology of today like smartphones in which you can take photos and shoot videos anywhere and at any time this is a problem during the evacuation of an airplane. The video of the evacuation of the flight 383 should not have been filmed at all. The crew should be instructing the passengers to turn their cellphones off. Although this is not shown on the video investigated in this case study, another video from a Qantas aircraft emergency evacuation on the 6th of August 2015 (Chan, 2015) show the crew telling the passengers to turn off their cellphones and in some cases they do, and the video therefore stops.

The people onboard show signs of stress or that they are stressed out of the situation when it was observed that people were screaming and shouting. The passengers yelled and pushed forward to the opened exits. However, there was an even larger number of passengers that were observed to have a calm behaviour much like the calm behaviour passengers have when boarding and deboarding an aircraft under normal circumstances.

From the video and from Figure 4 it can be seen that passengers did bring with them their luggage similar to what the passengers did in flight 405 as discussed in previous section. This ranges from the small handbags to the larger carry-on luggage.

Both of the cases examined demonstrate the potential for baggage being collected and for extended evacuation times. It is assumed that the presence of this baggage contributed to these extended times. This will now be explored.

Figure 4. The evacuation of American Airlines flight 383 (NBC News, 2016)

6 Simulation and scenarios

As discussed in previous section, a significant issue during aircraft evacuations is the passengers bringing their hand luggage. It is difficult to put a number on how many of the passengers will bring their luggage during an evacuation. In this case it is not relevant because the study is about the impact or difference in results when bringing luggage in comparison with not bringing luggage. The small-scale trial simulations (rapid deplaning) in this study will be done with 50 % of the passengers bringing their luggage compared to none of the passengers bringing their luggage during evacuation.

The flow through the doors is assumed here to not impact significantly the results, and this is because as it is later shown from the simulations there is no queue formed by the doors; in contrast, the occupants get stuck in congestions in the aisle. The flow through the doors is therefore assumed that it will not significantly affect the total evacuation time. The exclusion of this flow also enables us to focus attention on the presence and impact of the luggage on performance. It is acknowledged that slide performance may have an impact in some scenarios; however, we focus here on those scenarios where the internal dynamics dominate.

6.1 90 second trial

The 90 second trial will be done with the same criteria as given in Appendix J, Emergency Demonstration in the Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (European Aviation Safety Agency, 2012) which gives the following criteria for the passenger load:

- At least 40 % of the passenger load must be females
- At least 35 % of the passenger load must be over 50 years of age
- At least 15 % of the passenger load must be female and over 50 years of age
- Three passengers must carry infants 2 years old or younger. In 90 seconds test the infants are represented by life-size dolls.
- Only 50 % of the exits that meets the standards for emergency evacuation usage may be used. The other 50 % may not be used at all and are simulated as blocked or unusable.

6.2 Rapid deplaning

In the rapid deplaning scenario only one door is available for evacuation in the scenario. The door is in that case connected to the airport by a passenger-loading bridge/jetbridge; i.e. downstream flow constraints would not have had a significant impact, such as passenger hesitation entering the slide.

Inputs in this scenario is generally based on the data provided from the small-scale trials in section 7. The rapid deplaning scenario is an emergency scenario which the small-scale trials do not represent. However, the common behaviour for a rapid deplaning, for those scenarios who do not indicate any type of emergency, is a calm deplaning like when boarding an aircraft. The walking speeds, with and without luggage, and delay times caused by unfastening of seatbelts and getting up from the seats are used in the simulations.

The configuration of people is of the same gender and age throughout the simulation which translates to all the occupants being in good health like in the experimental data provided from the small-scale trial. The difference in the simulation being that gender and age does not matter when using the walking speed distribution from the small-scale trails which covers all the participants of different age and gender.

When simulating the passengers collecting their luggage, the data from the small-scale trial with walking speed with luggage will be used. The comfort distance will be changed from the runs that are without luggage because people tend to keep a larger distance when luggage is present in front of them which is an option available for Pathfinder but not explicitly represented in FDS+Evac.

The configuration of the aircraft consists of an aisle width of 0.63 meters for Pathfinder and 0.8 meters for Evac throughout the simulations of rapid deplaning. 0.63 meters is the largest aisle width available for the A320 and since 0.63 meters was the smallest aisle width used in FDS+Evac, due to the larger body sizes of the agents, an aisle width of 0.8 was chosen partly to fit the mesh used to draw the geometry and partly to get the effect of an wider aisle width. The purpose here is to see the difference when using only one exit and the impact the handling of luggage has on the deplaning.

6.3 General assumptions

The evacuations models were configured accordingly to previous section 6.1 and 6.2. The regulations in which the 90s scenario is presented provided the distribution of passengers and the evacuation condition but no data on pre-evacuation time and walking speed. The rapid deplaning scenario provided walking speed and pre-evacuation time.

6.3.1 Geometry

The geometry was built in Pyrosim (Thunderhead engineering, 2018) which could be used as a GUI to build geometric layout in both Pathfinder and FDS+Evac. A CAD file from Airbus was used to create a replica of an A320 with an accuracy within 10 centimetres (Airbus, 2018). In Pathfinder the geometry of the provided drawings from Airbus could be used without changing anything to fit the models standard configuration. Both an isle width of 0.48 meters and 0.63 meter was used and tested. In Evac however an aisle width of 0.48 meter could not be used since the standard configuration of the occupant sizes could not fit in that narrow space. In Evac an aisle width of 0.63 meters (which is the largest standard aisle width in a A320) and 0.8 meters were used. For the small-scale trial 0.63 meters aisle width was used for Pathfinder and 0.8 meters for Evac. The increased aisle width of 0.8 meters in Evac is used to fit the mesh which is set to 0.4 meters grid.

6.3.2 Occupant body size

One of the main parameter that differentiate the simulation inputs in Pathfinder and FDS+Evac was the body sizes of the occupants. As mentioned in the previous section the aisle width had to be changed depending on the occupant body size used. It was also tested how much the impact on the total evacuation time had on using different body sizes. At first the standard body sizes in both models were used. Pathfinder uses a fixed value and FDS+Evac uses a uniform distribution depending of age and gender. The body sizes in FDS+Evac were also used in Pathfinder and vice versa to test the impact on the total evacuation time the boy sizes have on each model.

6.3.3 Walking speed

In Pathfinder the walking speeds from the IMO profiles are used since there is no research done on the walking speeds for the 90 second scenario. The IMO (International Maritime Organization) profiles are based on the *Revised Guidelines on Evacuation Analysis for new and Existing Passenger ships* (Thunderhead Engineering, 2018). The data from the small-scale trial is not applicable in this case due to the trial not being done in an emergency evacuation scenario which the IMO profiles are. FDS+Evac uses the IMO walking speeds as default.

For the rapid deplaning scenario, the walking speeds provided form the small-scale trial will be used. The data used is presented in section 7.1.

6.3.4 Comfort distance/social force

When simulating occupants carrying luggage one parameter beyond a reduction in speed is the comfort distance in Pathfinder or the social force in Evac that should be theoretically impactful. When carrying luggage, people tend to stay further away than without luggage. To simulate this behaviour the comfort distance or the social force have been changed from the default settings to 0,3 meters in both Evac and Pathfinder. The value 0,3 meters is an estimation to see the impact it has on the results.

6.4 Trials

The following trials, as seen in below *Table* 3 have been simulated and the default configuration has been used where the description does not mention the specific configurations in use.

Table 3. Overview of simulation trials

Trail	Description
Trail 1	90s trial with aisle width 0,48 meters for Pathfinder and 0,63 meter for Evac.
Trail 2	90s trial with increased aisle width of 0,63 meters for Pathfinder and 0,8 meter for Evac.
Trail 3	90s trial with increased body size for Pathfinder and decreased body size for Evac. Aisle width 0,63 meters for both Pathfinder and Evac.
Trail 4	Small-scale trial with no luggage.
Trail 5	Small scale trial with luggage.
Trail 6	Small-scale trial with luggage and no changed comfort distance/social force.

7 Small-scale trial

In this section a small-scale trial done by the NRC (National Research Council of Canada) will be reviewed and the data will be compiled (Gwynne, o.a., 2017). The research data will be later used in the evacuation simulations.

The trial was done in a research facility in Canada where the NRC had built a mock-up of a part of an aircraft which in this case was a part of an Airbus A320. The trial was done during a non-emergency situation and comprised of the boarding and deplaning process. All of the participants were members of the NRC staff and were well informed of the trials and its procedure. The staff were of working age and without any kind of disability. The trial involved the usage of luggage, both hand-held luggage and rolling luggage. Due to the safety of the participant the luggage was fairly light packed.

The trials were done both modular and with a flow. In the modular part, the participants were provided instructions with markers placed out in the mock-up. The markers were there for the modular part of the trial, the participants knew where to go and which tasks they should perform. The trial only involved single individuals at a time. After the modular part was done it could become a flow trial were all the tasks were done without any stop and interruption but with reminders about the micro-behaviours they should perform.

The purpose of the trial was to have more data collected to be used in aircraft movement simulations and to see the difference on boarding and deplaning the aircraft with and without luggage. The movements were predefined from a series of micro-behaviours, which is why the trial firstly consisted of a modular part to have the participants rehearsing the movements. The microbehaviours that are relevant to the scenarios in this thesis are:

- Unlocking seatbelt.
- Leaving seat.
- Collecting luggage form overhead compartment.
- Traversing aisle with luggage.

7.1 Input data

In Table 4 the data used as inputs in the simulations are presented as follows: average (sd, N) *median[min-max]*. The values used is the highest values with different seat pitches. Since it is not known which seat pitch is used in the Airbus the highest values are used for a worst-case scenario.

Table 4. Small-scale trial data

Input	Value [s]
Unfasten seat belt	1.9 (0.7, 60) *1.8 [1.0 - 6.4]*
Leaving seat	2.5 (1.0, 64) *2.2 [1.0 – 11.7]*
Collecting bag stored in the overhead bin	7.0 (1.8, 90) *7.0 [0.9 – 10.2]*
Row speed (with luggage)	0.52 (0.14, 92) *0.49 [0.27 – 0.93]*
Row speed (without luggage)	0.56 (0.14, 93) *0.53 [0.28 – 0.97]*

8 Results

In this section the results for the simulations are shown. The results are presented as a comparison against each other for each trial where the results area an average of the 25 repeated simulations performed to achieve a convergence under 2 %. In Table 5 the results from all the simulations are presented.

Table 5. Simulations results

Trial	Pathfinder Avg, std *(min - max)* [s]	Evac Avg, std *(min - max)* [s]
Trial 1 – 90s Deplaning	126, 5.0 *(118 – 137)*	116, 13.8 *(97 – 149)*
Trial 2 – 90s Deplaning increased aisle width	104, 4.5 *(95 – 112)*	107, 7.8 *(93 – 125)*
Trail 3 – 90s Deplaning increased/decreased body sizes	106, 5.3 *(98 – 118)*	110, 10.4 *(91 – 139)*
Trial 4 – Rapid Deplaning without luggage	526, 10.0 *(512 – 550)*	525, 26.4 *(472 – 589)*
Trail 5 – Rapid Deplaning + luggage	571, 27.2 *(531 – 641)*	538, 24.0 *(493 – 588)*
Trial 6 – Rapid Deplaning + luggage with no social force/comfort distance	556, 23.4 *(521 – 613)*	545, 18.3 *(500 – 578)*

8.1 Trial 1 – 90s Deplaning

In this section the results of trial 1 are presented. In Figure 5 below the distribution of total evacuation time is presented and in Figure 6 the average number of occupants exiting as function of time is presented for Pathfinder and Evac.

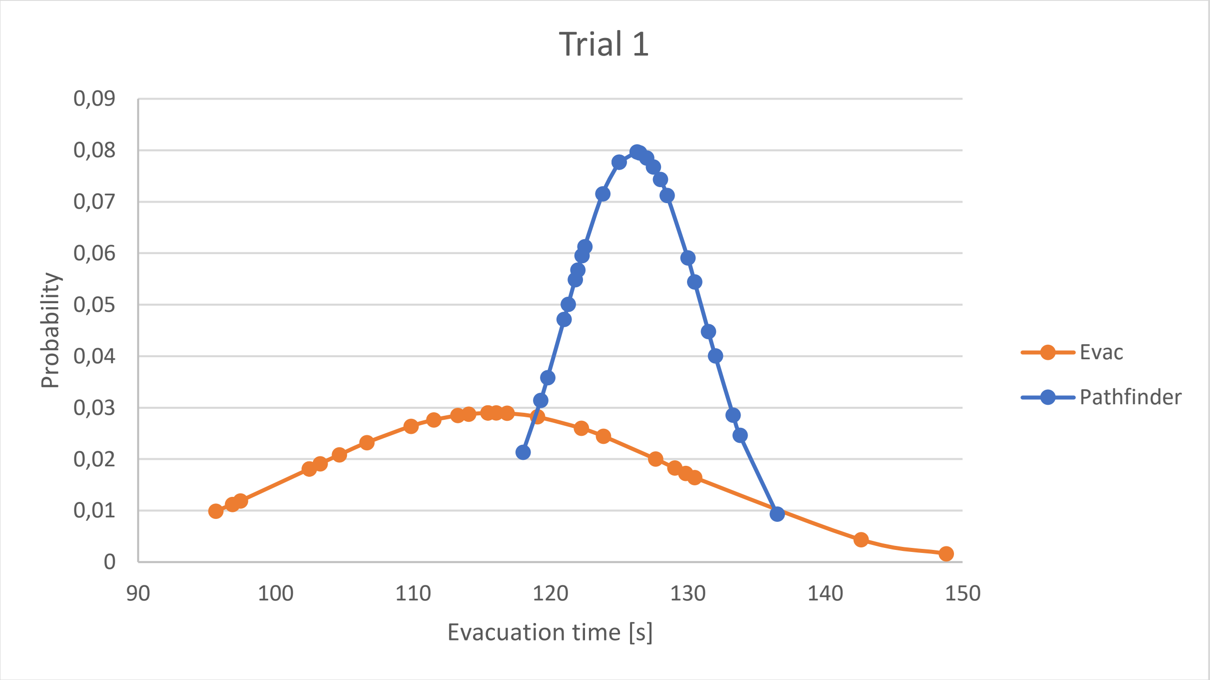

Figure 5. Normal distribution over Trial 1 simulations in Pathfinder and Evac

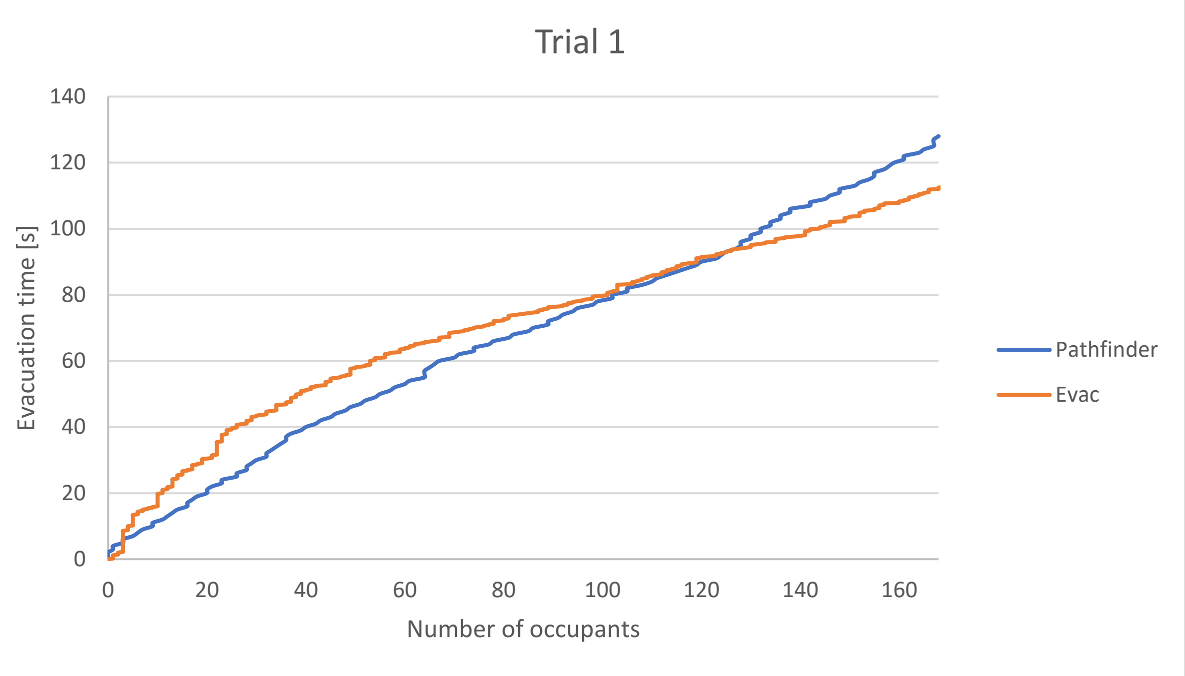

Figure 6. Average arrival time curve for Trial 1 in Pathfinder and Evac

8.2 Trial 2 - 90s Deplaning increased aisle width

In this section the results of trial 1 is presented. In Figure 7 below the distribution of total evacuation time is presented and in Figure 8 the average number of occupants exiting as function of time is presented for Pathfinder and Evac.

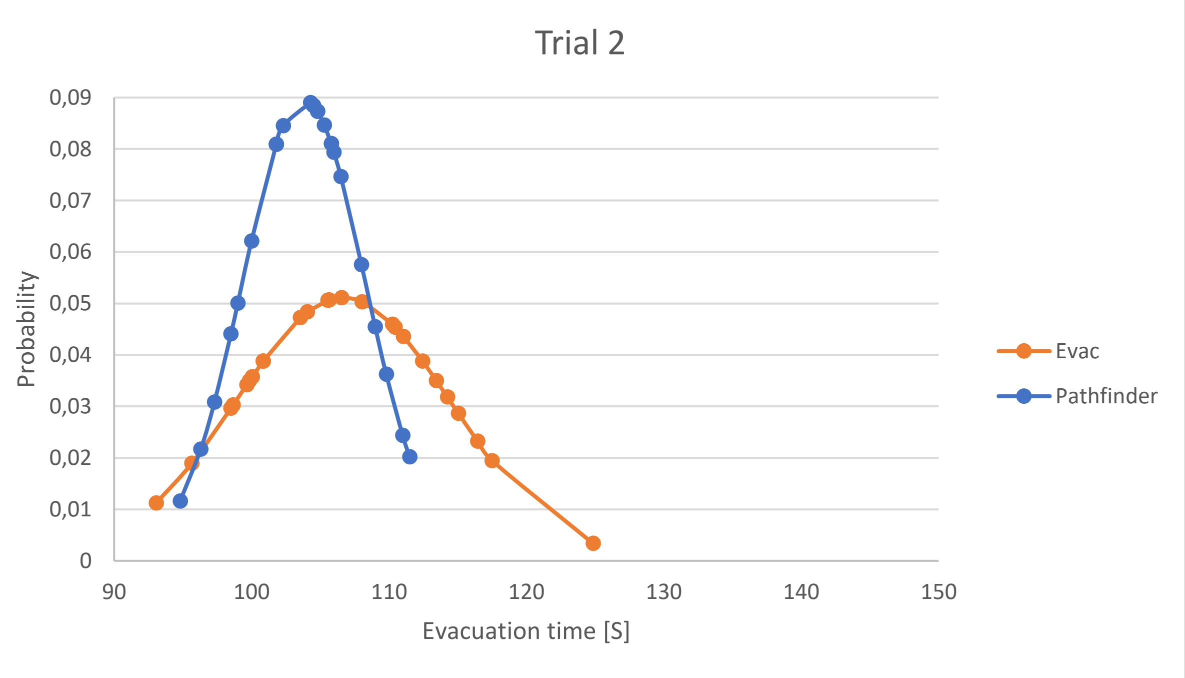

Figure 7. Normal distribution over Trial 2 simulations in Pathfinder and Evac

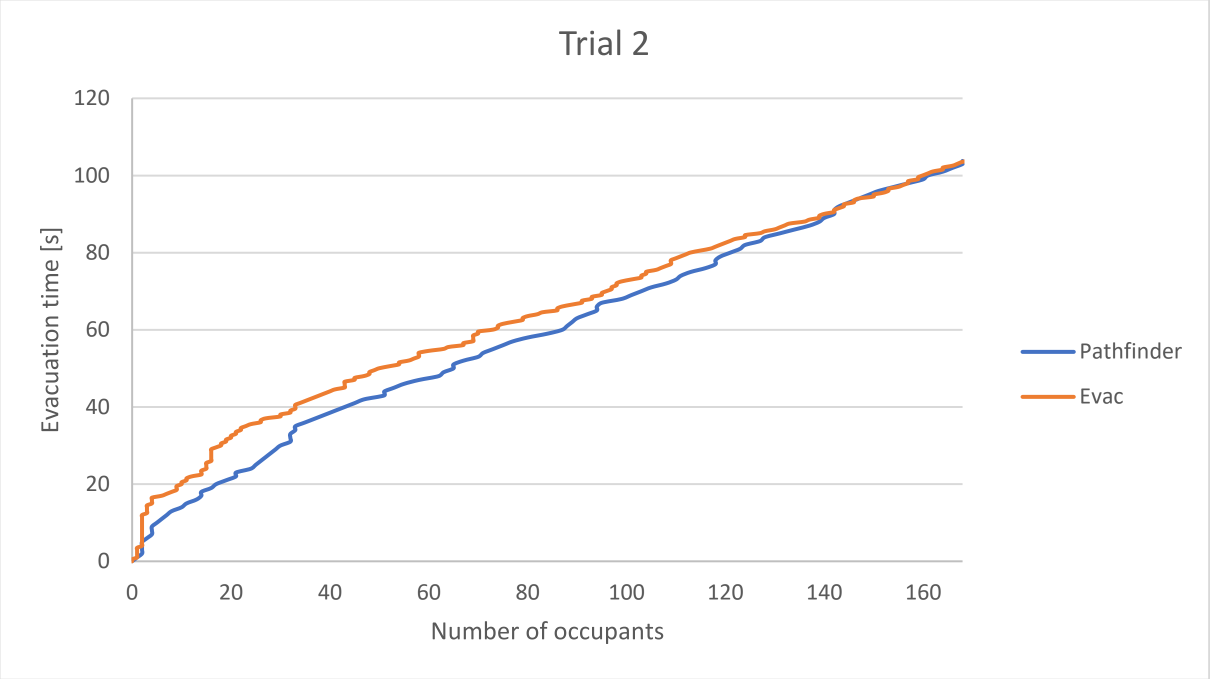

Figure 8. Average arrival time curve for Trial 2 in Pathfinder and Evac

8.3 Trial 3 - 90s Deplaning increased/decreased body sizes

In this section the results of trial 1 is presented. In Figure 9 below the distribution of total evacuation time is presented and in Figure 10 the average number of occupants exiting as function of time is presented for Pathfinder and Evac.

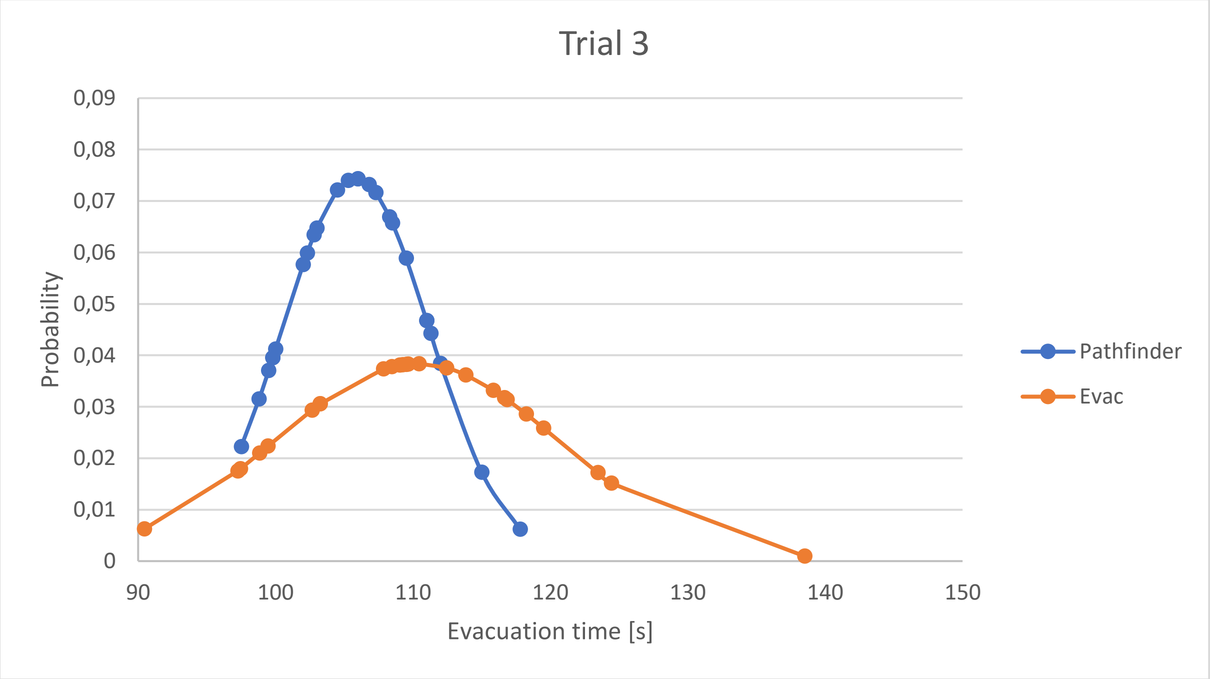

Figure 9. Normal distribution over Trial 3 simulations in Pathfinder and Evac

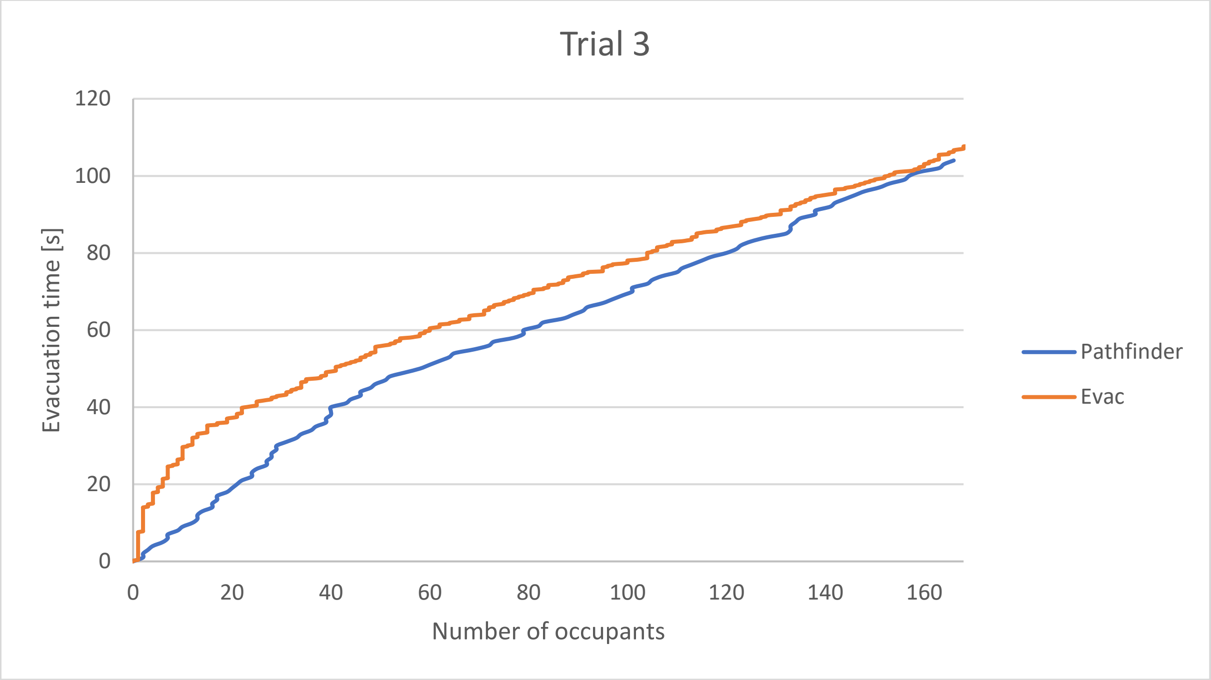

Figure 10. Average arrival time curve for Trial 3 in Pathfinder and Evac

8.4 Trial 4 – Rapid Deplaning without luggage

In this section the results of trial 4 is presented. In Figure 11 below the distribution of total evacuation time is presented and in Figure 12 the average number of occupants exiting as function of time is presented for Pathfinder and Evac.

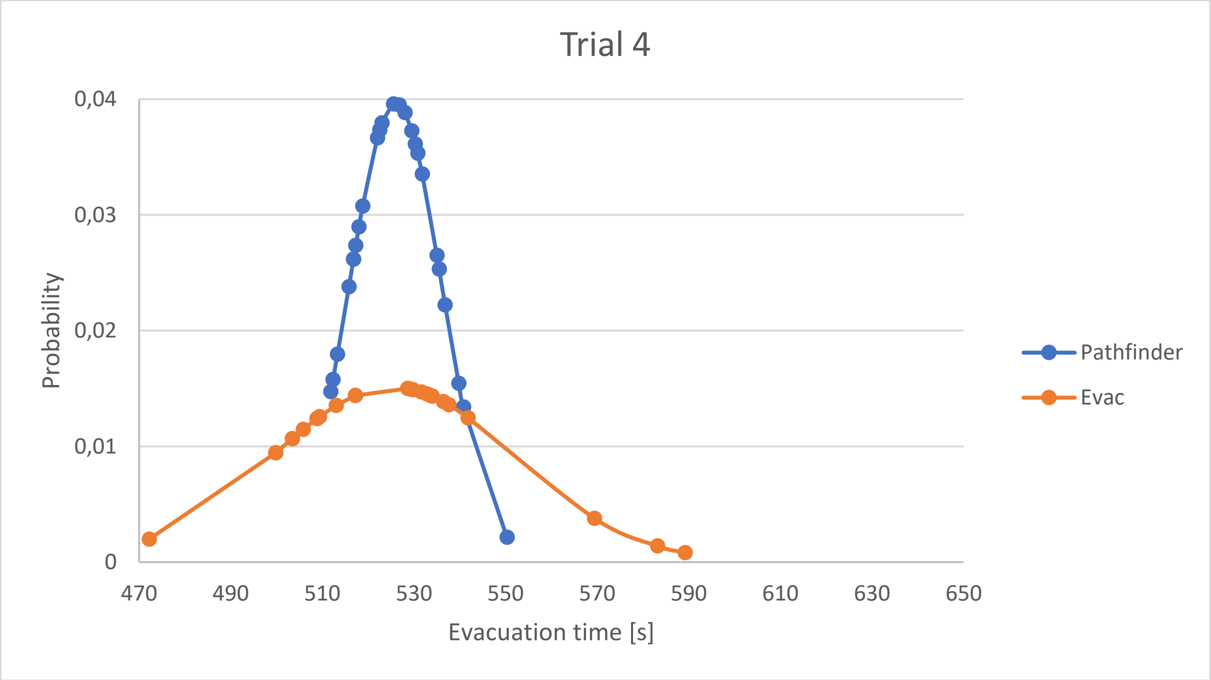

Figure 11. Normal distribution over Trial 4 simulations in Pathfinder and Evac

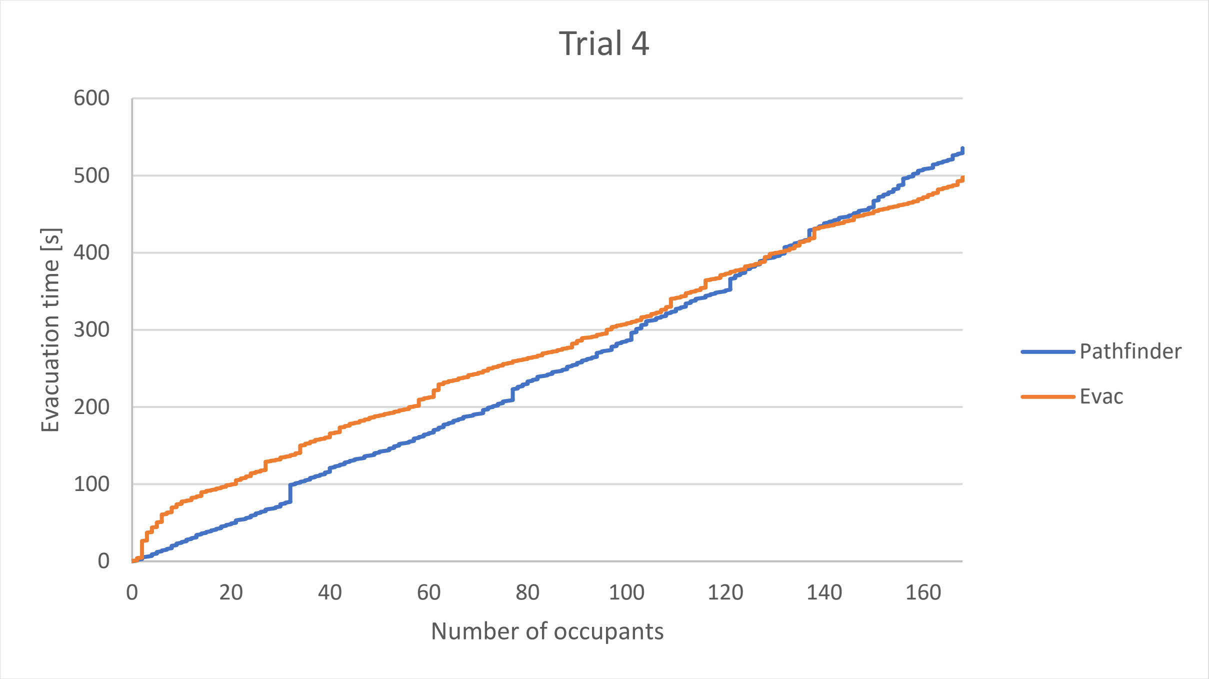

Figure 12. Average arrival time curve for Trial 4 in Pathfinder and Evac

8.5 Trial 5 – Rapid Deplaning + luggage

In this section the results of trial 1 is presented. In Figure 13 below the distribution of total evacuation time is presented and in Figure 14 the number of occupants exiting as function of time is presented for Pathfinder and Evac.

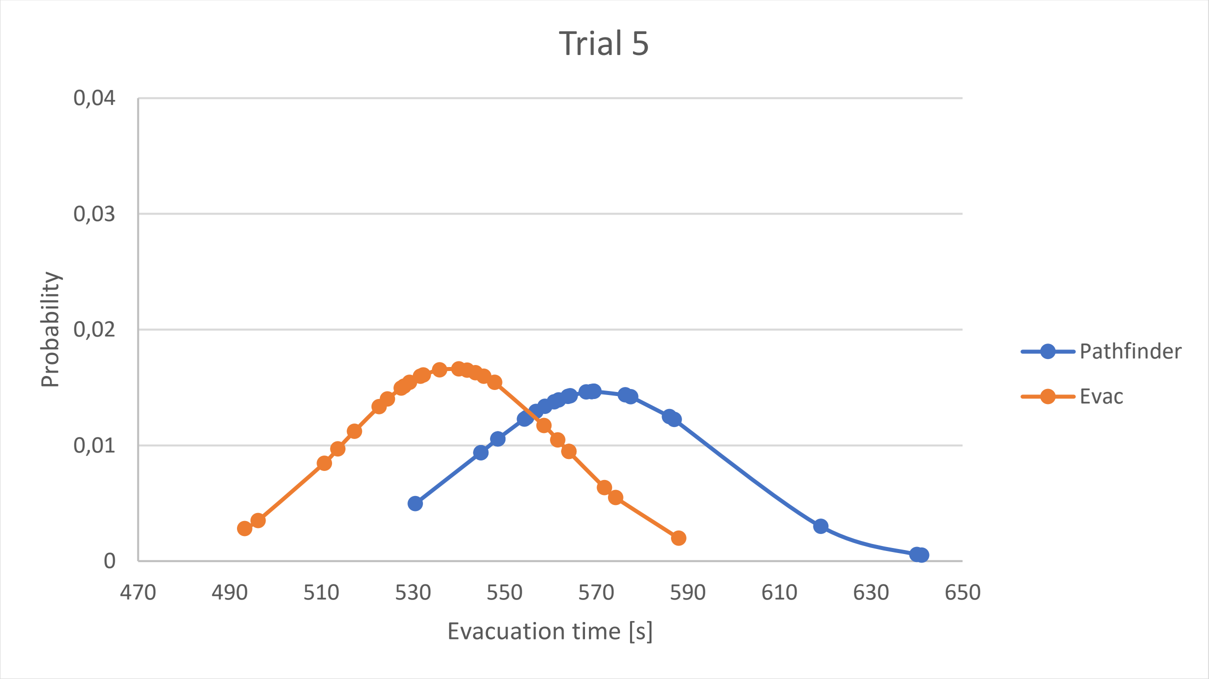

Figure 13. Normal distribution over Trial 5 simulations in Pathfinder and Evac

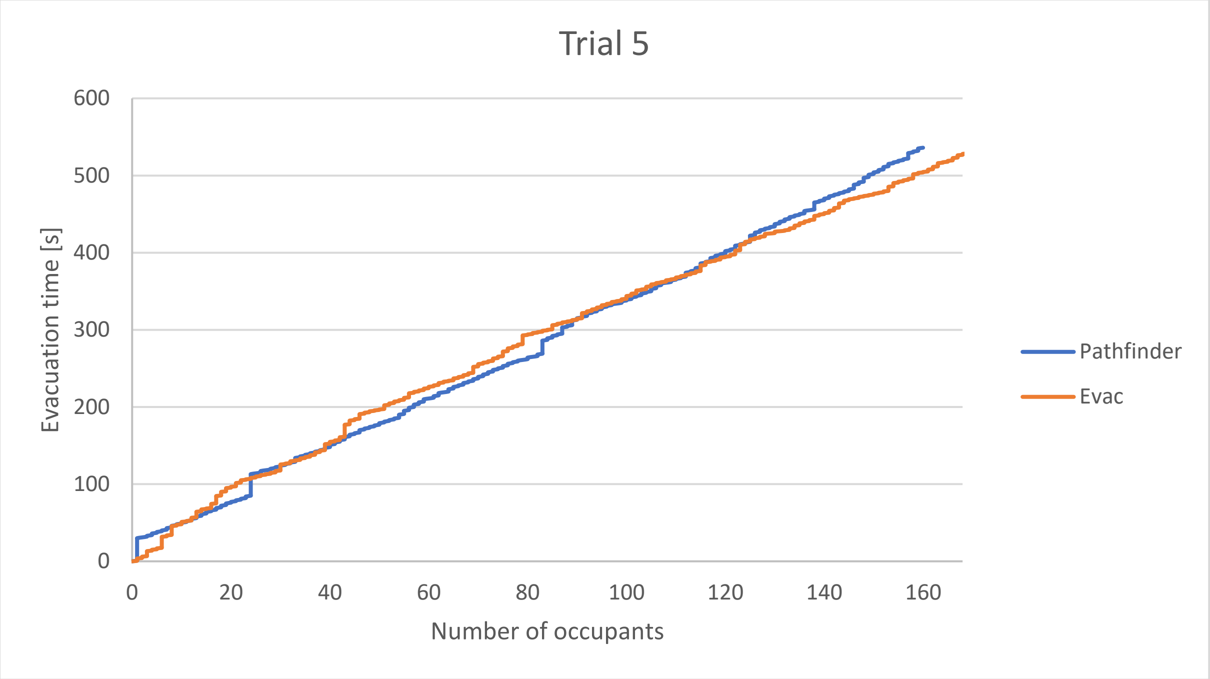

Figure 14. Arrival time curve for Trial 5 in Pathfinder and Evac

8.6 Trial 6 – Rapid Deplaning + luggage with no social force/comfort distance

In this section the results of trial 6 is presented. In Figure 15 below the distribution of total evacuation time is presented and in Figure 16 the average number of occupants exiting as function of time is presented for Pathfinder and Evac.

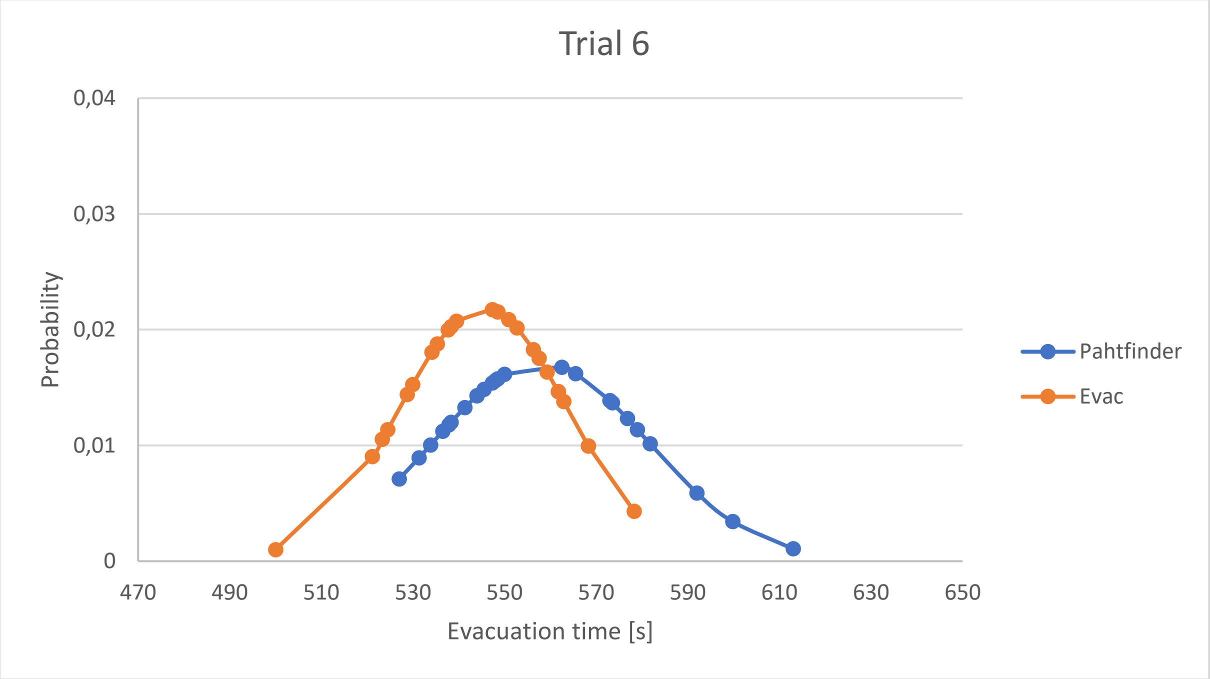

Figure 15. Normal distribution over Trial 6 simulations in Pathfinder and Evac

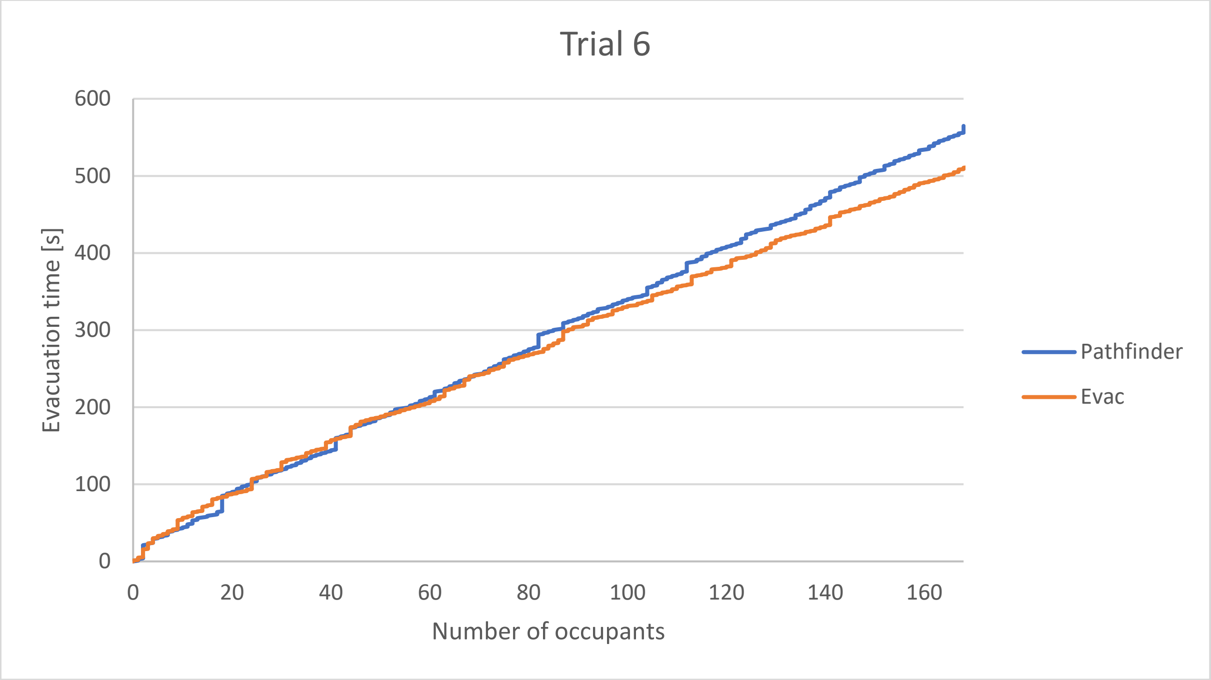

Figure 16. Average arrival time curve for Trial 6 in Pathfinder and Evac

9 Discussion

In this section the results from the simulations and the sensitivity analysis will be discussed for both models.

9.1 Pathfinder results discussion

Pathfinder possess all the necessary tools to perform a 90 second certification simulation. It is easy to distribute to population which is specified in the regulation. When using the IMO-profiles the results are satisfactory. What mainly influence the total evacuation time is not in this case the walking speed rather the narrow geometry which easily causes congestion. This can be seen in the results where the size of the agents and the width of the aisle has an impact on the total evacuation time. It lacks however the option to explicitly simulate an adult holding an infant in the case of 90s scenario where it is a part of the regulation to carry an infant (life-sized doll) during the tests. In that case there is no data available therefore there cannot be any conclusion to if the person would walk slower or faster. It may also be in that case that the person holding an infant will be prioritised to exit the aircraft first.

With the default settings of bodies size Pathfinder is capable to produce results with the narrow geometry from the aircraft. Pathfinder produces a difference in results depending on the aisle width and depending on the body size of the occupants but is capable to use the default settings of body sizes in a narrow geometry.

In the given scenarios, when luggage is present the total evacuation time increases with an average of 45 seconds or 9 % increase of average total evacuation time and it could be even more if also simulating the collection of luggage from the overhead bins.

9.2 FDS+Evac results discussion

Using the standard configurations given in the model, limitations are present in the minimum space needed to allow movement within the geometry. When using the standard body sizes in the model, the occupants get stuck when using the standard geometry for the Airbus with the aisle width of 0,48 m. It is possible however to reduce the body sizes or increase the space available for movement in the aisle. The second choice has been made in order to have a realistic agent-to-agent interaction.

Evac is showing an increase of 13 seconds or 2,5 % increase of average total evacuation time when the luggage is present. As mentioned in previous section 9.1 the time could be more due to the missing function of having the occupants going to the aisle and wait there for a short amount of time.

9.3 Comparison

The distribution shows generally a wider distribution of results in Evac compared to Pathfinder which means that – with the given input - FDS+Evac generates a wide spectrum of results whereas Pathfinder generally generate packed distributed results. What this means is that FDS+Evac, given the inputs in use, tend to be more sensitive to changes than Pathfinder is which in this case means in all of the trials changes in the seat allocations of passengers i.e. changes in walking speeds. What also can explain the wide spread of results for Evac is the use of a distribution of body sizes which is built in as a default in FDS+Evac whereas in Pathfinder the body sizes are by default a constant value. This gives FDS+Evac another value that changes beyond the walking speeds which could explain the big differences between Pathfinder results and FDS+Evac results.

Although there are no tests done in real life to compare the simulated results (except the 90s trial which has no data except a criteria to achieve 90 seconds) FDS+Evac provided a total evacuation time in a reasonable order of magnitude despite its spread of results. In the given configuration, FDS+Evac seems to rely significantly on the users' capability to insert inputs (in particular given the issues associated with the representation of narrow spaces) whereas Pathfinder seem to be less sensitive to input changes. FDS+Evac and Pathfinder could both be used for certification purposes where is necessary to investigate the evacuation time against the 90 seconds criteria. Evac and Pathfinder can also be used for recreating evacuations done in real life where data on the evacuation time is available.

The first issue a user will notice is the ease of use when comparing Pathfinder to FDS+Evac in this case. When starting simulating aircraft evacuation in Pathfinder a more precise geometry can be used where the agents in Pathfinder can adapt to the narrow geometry of an Aircraft. The geometry can be build using Pyrosim (Thunderhead engineering, 2018) which can be used for both Pathfinder and FDS+Evac which gives the models an advantage that the geometry can be reused. The geometry used in this case had to be rebuild for FDS+Evac after using it in Pathfinder due to the large difference in size of the occupants in the models where FDS+Evac has larger occupants. The minimum recommended width that the occupants can pass through in FDS+Evac should be at least 0.7 (Korhonen, 2018) but the results showed that a width of 0.63 meters also allows movement. This can explain the wide range of total evacuation time for FDS+Evac in Trial 1 compared to Trial 2 due to usage of a smaller width than recommended. The cause may be the collision avoidance mechanism built in the models where in FDS+Evac for it to work as intended the width of the aisle in this case must be wider than 0.7 meters. In this case Pathfinders collision avoidance mechanism works with the narrower aisle width but may work even better when the width of the aisle increases as the results are showing from Trial 1 and 2. Both of the models uses rigid bodies and can not simulate people squeezing in between other people in the limited space of an aircraft which is an another limitation for both of the models. This would decrease the extent of the congestion and may therefore increase the total time of evacuation.

The aspect the models have in common concerns body size and movement in the aisle width, i.e., it is often not possible to simulate the narrowest geometry of an aircraft with the default settings of body sizes. It is possible to have the exact geometry from the aircraft and reduce the body sizes to achieve an evacuation time under 90 seconds in certification purposes which is a similar case as Trial 2 shows. Trial 2 increases the aisle width from 0.48 meter to 0.63 meters in Pathfinder and from 0.63 meters to 0.8 meters in FDS+Evac which gives the same effect as decreasing the body sizes according to trial 3. The conclusion from the results of decreasing the body sizes and widening the aisle is that the total evacuation time decreases. Why the time decreases are because the congestion decreases, and people can move more freely. When leaving the rows, the occupants have more room to squeeze into in the aisle.

Both models show an increase in total evacuation time in the rapid deplaning scenario when luggage is handled by the occupants but the difference in time is larger in Pathfinder than in FDS+Evac. In Pathfinder the increase of total evacuation time was almost 8 % whereas in FDS+Evac it was only 2.5 % increase. As mentioned before, it could be larger if the occupants collecting the luggage form the overhead bins could be simulated explicitly. The increase in total evacuation time would also be larger if the small-scale trial had been done with more

heavy packed luggage as it is in reality. This was not possible to recreate such realistic scenario due to ethical reasons and risks for injuries.
When introducing the reduced walking speed, longer pre-evacuation time and changed comfort distance into Pathfinder the spread of results widen but the results in FDS+Evac gets narrower as can be seen in Figure 13 and Figure 15. The spread in Pathfinder results is however not that significantly large as FDS+Evac in the rest of the trials and can be explained by the introduction of more changing variables in which then Pathfinder does not produce results with a narrow spread. In comparison with the 90s trials the only parameter that varies in the trials is the seat allocation of the occupants and their walking speeds. In the rapid deplaning trials the parameters that is subject to change is the seat allocation of the occupants and their walking speeds and pre-evacuation time consisting of three different parts.

When carrying luggage usually the passengers behind tend to have a longer distance between the passenger carrying. It is not possible to change the comfort distance explicitly in FDS+Evac but however it is possible to change the social force parameter if it is possible to translate the comfort distance to a social force. In this case the parameter that was changed was the spatial extent of the social force in FDS+Evac and the comfort distance in Pathfinder. The social force parameters in FDS+Evac has more variables to consider than in Pathfinder and may to be studied even further to see its impact. Trial 5 and 6 shows a difference in the spread of results in both Pathfinder and FDS+Evac where it is wider in Trial 5 than in 6. In Pathfinder the comfort distance is set in this case by a constant value and the spatial extent parameter in FDS+Evac is also set to a constant value. Why FDS+Evac produce such results may be to that extent that the social force model does not make great impact in such narrow geometry where the occupants almost have nowhere else to go. Or the results may depend on the users less inexperience of the social force model in Evac which in that case needs to be investigated further in the future.

Both models are able to reproduce congestion in the aisle which is especially shown in the rapid deplaning scenarios. The models show similar behaviour when congestion starts in the aisle compared to the microbehaviours studied in the small-scale trial (Gwynne, o.a., 2017). The typical behaviour is passengers standing and waiting in their rows before the congestion clears in front of them before they step out. The simulations also show some of the passengers hesitate both in the aisle and in the rows when trying to pass by. What Evac is missing and what Pathfinder has but requires a lot of manual work is the handling of luggage i.e collecting the luggage in this case from the overhead bins. Pathfinder has the function to force the occupants to go to a specific waypoint which would be in this case in the aisle by the overhead bin. This would cause even greater congestion for a short amount of time but presumably enough to affect the total evacuation time. This option is however not available in Evac and were therefore not tested in this thesis. It should however be tested in models such as Pathfinder that allow behavioural itineraries and possibly be validated against real trials for future research purposes.

An issue that both models are missing and may be in otherwise presented in a reduced walking speed is the low height to the ceiling above the seats which may forces most of the passengers to crouch and that may have an impact on the walking speed when leaving the seats and when using the overwing exits. In these simulations the low height to the ceiling has not been considered due to the models not considering of it (i.e. they represent the movement within the aircraft in 2D). Pathfinder has an option built in to change the height of the occupants and but this does not impact the movement in the 2D space (Thunderhead Engineering, 2018). There are no experimental data on this matter and its impact on the total evacuation time is largely unknown, but it can be assumed to have an impact in increasing the time.

10 Conclusion

Pathfinder and Evac have been successfully used to simulate aircraft evacuation. Their calibration depends however substantially on the user to adjust the parameters and implement reasonable inputs. In particular, using the default settings in continuous models, narrow geometries may create issues in the simulation, and models may have issues in producing realistic results to real-life. The user has therefore to act on the body size of the occupants and the geometries in order to calibrate the model. Both models also make use of 2D representation of the space which is not entirely representable of the narrow and low height space of an Aircraft. In this case the results would be a further decrease in total evacuation time.

Both models make use of rigid bodies which means that the occupants in the simulations will not be able to squeeze in between other people and/or narrow spaces which is not representable in an Aircraft evacuation environment.

When evacuating with luggage both models simulate a higher total evacuation time than without luggage. In conclusion the presence of luggage will make the total time for evacuation higher in Pathfinder and Evac which can be reflected in real-life. The simulation of the presence of luggage is easier to implement explicitly in models such as Pathfinder which allow to insert behavioural itineraries and actions/delays during the passage of time.

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Appendix A

Convergence of model results

Each simulation was executed independently and was examined for convergence if sufficient simulations had been done. In below Figure 17 the convergence for Pathfinder is presented and in Figure 18 the convergence for Evac is presented. The total number of runs that has been made is 25 and this was made to obtain a convergence under 1 % for at least 10 consecutive runs.

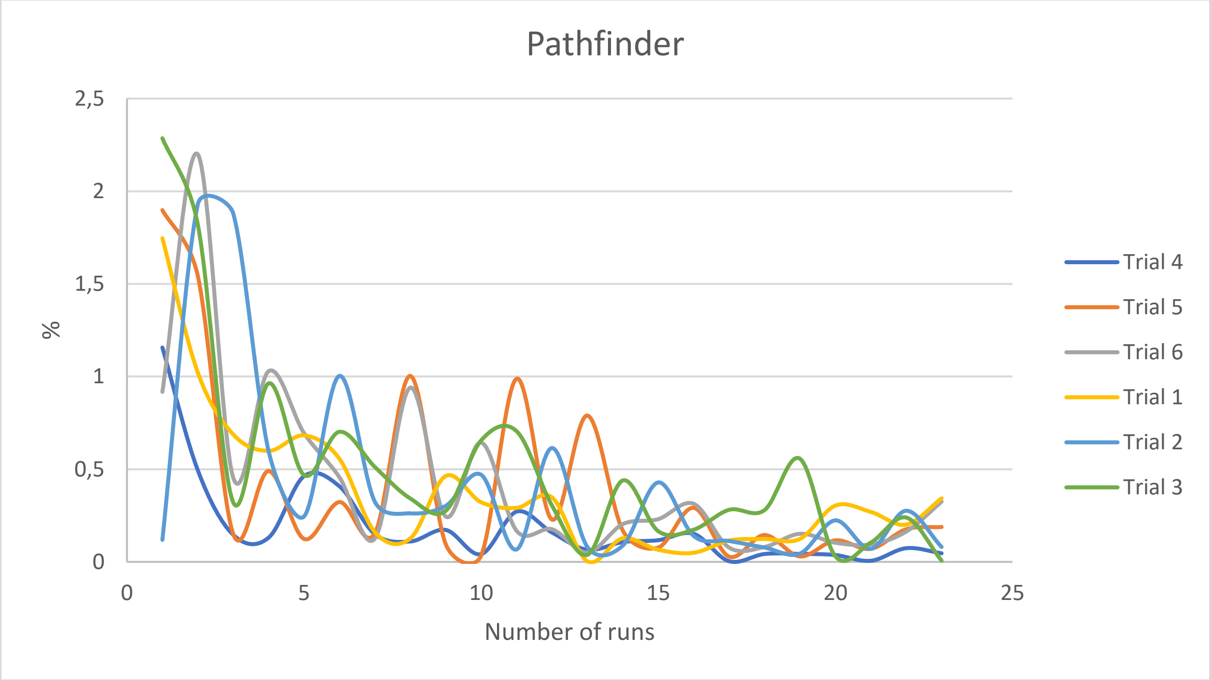

Figure 17. Pathfinder convergence

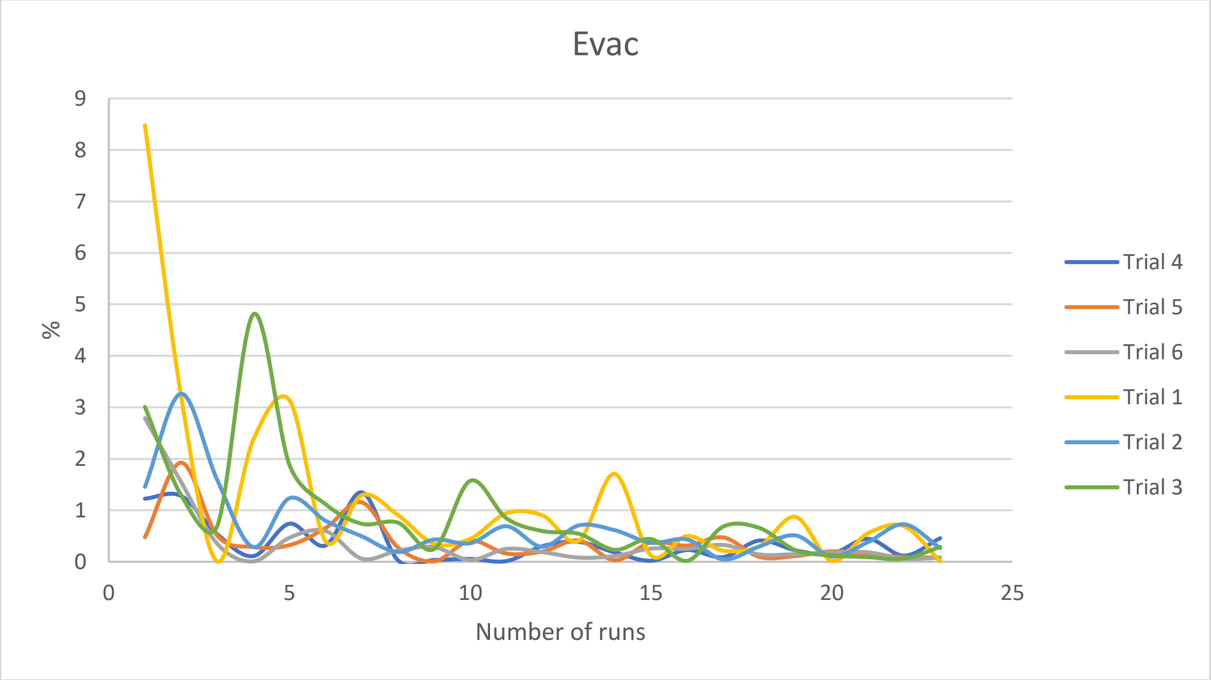

Figure 18. Evac convergence