Mestrado em Engenharia Informática
Dissertação
Relatório Final

EvacSafeX: A Multi-Agent Model for Aircraft Evacuation Simulation

Julho, 2016

João Simões
jbsimoes@student.dei.uc.pt

Orientador:
Prof. Dr. Tiago Baptista
baptista@dei.uc.pt

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João Simões
jbsimoes@student.dei.uc.pt

Orientador:
Prof. Dr. Tiago Baptista
baptista@dei.uc.pt

Júri:
Prof. Dr. Raul Barbosa
rbarbosa@dei.uc.pt
Prof. Dr. César Teixeira
cteixei@dei.uc.pt

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“O que for, quando for, é que será o que é”

Alberto Caeiro, in *”Poemas Inconjunto”*

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João Simões
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Abstract

Throughout the last decades, several simulation models have been proposed in an attempt to reproduce aircraft evacuation scenarios and provide an alternative to real certification trials. Furthermore, simulation models have been proven to be a useful tool when designing new aircraft enclosures. Among these, the airEXODUS model has seen widespread application and validation, being successful in predicting past certification trials and examining issues related to aircraft enclosure layout.

This work introduces EvacSafeX, a multi-agent model centered around proper representation of human behaviour in aircraft evacuation scenarios. EvacSafeX finds its inspiration in complex systems and in the airEXODUS model, seeking to make complex interactions and behaviour emergence from individual modeling of human passengers. The model also takes novel approaches to represent human behaviour and passengers movement along the aircraft cabin.

EvacSafeX adopts a perception-action approach to represent agent's capabilities, following a behavioral model defined by a rule list brain. Passengers are also characterised by both physical and psychological attributes identified as the most relevant in evacuation scenarios. In addition to the many components already included in the model, its generic architecture allows other ones to be easily incorporated.

The components implemented beforehand in EvacSafeX prototype were verified through a set of validation experiments. At first sight, it was observed a significant sensitivity of some passenger's personal attributes, representative of their influence in real life cases. Furthermore, the proposed model demonstrated a high flexibility and diversity in the representation of passenger's behaviour, leading to an emergence of several different phenomena observed in real evacuation scenarios. Finally, promising results were obtained in an attempt to reproduce real certification demonstrations results and other experiments conducted with state of the art models.

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Chapter 1

Introduction

In this chapter, it will be firstly presented the motivation behind this work. Then, the main goals will be described as well as the main contributions of this work to the state of the art. Finally, a brief description of the remaining document is presented.

1.1 Motivation

When designed or modified a new aircraft cabin layout, a validation process must be conducted to ensure passengers' security and effectiveness in emergency situations. Aspects like aisle width, seat pitch, the amount of aisles, the amount of evacuation exists and their corresponding positions are examples of aircraft characteristics that can influence the evacuation process [4, 5]. During the last years, several different cabin architectures have being proposed in an effort to increase passenger capacity [6], such as in low-cost flights. However, some security problems can emerge, being needed a credible validation of aircraft evacuation effectiveness.

For this purpose, regulation entities defined a set of rules to enforce security standards in aircraft evacuation scenarios. In Europe, these rules are known as Joint Aviation Regulations, while in the USA they are designated Federal Aviation Regulations. One of these rules (and probably the most well-known) defines a maximum evacuation time of 90 seconds with a maximum density configuration, a half of the total amount of emergency exits and in lightless conditions.

Given that these certifications are mandatory before deploying a new aircraft, several real evacuation simulations have been conducted by aviation industry. These certification simulations are performed in a real environment. In addition to 90-second time limit, a specified mix of passengers “in normal health” must be used as a way to represent the normal gender mix and age found on revenue flights. Crew members and passengers do not know beforehand which exits are available in the evacuation process. However, problems regarding to ethics, costs, and human volunteers are associated to this kind of demonstrations. Some studies found that almost 5 percent of volunteers in a certification process suffered injuries while evacuating [7, 8], mainly caused by jumping down inflate slides (height and friction), interaction between passengers and many other situations. Additionally, each demonstration usually has an associated cost of between $1,000,000 and $2,000,000 [9]. Furthermore, volunteers are neither under panic nor under environment constraints of real evacuation conditions such as fire, smoke and toxic gas leaks. Also, a single certification trial is required to pass in the certification process, being only covered a limited set of scenarios among those observed in real evacuation ones.

Over the past years, several mathematical and agent-based approaches have been explored and implemented with the purpose of simulating aircraft evacuation. Aircraft enclouser representation, passengers’ behaviour and interactions among them are core components when researching in this field [10]. Probably, the most successful simulator is airExodus proposed by E. R. Galea et. al. [11] which development began in 1989 with support from UK CAA and the aviation industry. AirExodus is an agent-based model with a master control in which a simulation clock defines agents and world changes along the simulation. It was object to a wide range of validation tests with real evacuation demonstration data, having been registred a high capability of successfully reproducing the overall evacuation performance [3]. Also, airExodus has demonstrated its ability to predict the evacuation performance when ajusted different components in an aircraft cabin (e.g. evacuation exit separation) [4, 12].

1.2 Goals

In this work, a new agent-based model — EvacSafeX — is proposed, as an effort to represent aircraft evacuation scenarios, taking airExodus model as major influence. A combination of agent-based and complex systems is used with the purpose of designing a system without any central control or supervision over the lower level components, while simultaneously searching for an emergence of complex global behaviour between passengers through individual capabilities of each one. Therefore, each passenger is fitted with a set of perceptions, actions, psychological and physical features.

EvacSafeX is designed under BitBang framework architecture developed by Tiago Baptista et. al. [2]. BitBang framework is inspired by complex systems and provides a wide range of components to sustain several different world definitions. As major advantage, these components are not controlled by any centralized system (there is no definition of simulation step) wherefore agents perceive, decide and act in an independent way.

Human behaviour representation is definitely the most important and complex component when exploring a new real life simulator due to the complexity inherent to natural processes and human behaviour. The EvacSafeX model focus essentially in a correct and flexible representation of different individuals' behaviour. It is expected that an user should be able to represent many distinct behaviour and hypothetical scenarios. Although airExodus includes a cabin enclosure under hazard conditions, this work is not actually focused on this component. Human behaviour representation without any hazard conditions (as observed in certification scenarios) is actually the main focus.

Definitely, there are no previous guarantees to a better or worst performance of the proposed model when compared to airExodus model or any other simulator already known. An effort will be focused to rise a model able to represent human behaviour and interaction in evacuation scenarios, always seeking for a efficient computational performance. Effectively, there are many factors which indicate that this kind of approach may be a reasonable alternative and good overall performance can be achieved with it.

1.3 Contributions

The main contribution of this work is effectively the proposed simulation model. It was developed in an attempt to reach the goals previously presented. Therefore, several contributions of this work can be highlighted:

- A multi-agent model which allows that many different behaviour observed in certification scenarios could be represented through a wide range of components already provided. Its flexible architecture make it possible that other individual's characteristics and capabilities may be incorporated, with the purpose of cover a wider range of behaviour in both real and certification scenarios.
- An autonomous algorithm that reduces some workload associated to a discretization of the navigation graph.
- An initial explicit representation of flight attendants in evacuation scenarios with a perspective focused on the individual instead of in the system as a whole.
- A simulation environment prototype that implements the proposed multi-agent model, providing a 3D graphical engine and physical engine. However, physical

engine is not already being used in the current prototype. In this way, it is possible to track all the evacuation process and validate individuals' behavior through an indispensable visual inspection.

- Several different experiments were executed in order to validate the proposed model. They showed an emergence of interesting behaviour, representative of the ones observed in real-life, and an ability of reproduce some certification demonstrations.

As main contribution, the proposed model prototype is made available to the community.

1.4 Roadmap

The remainder of this document is organized as follows: In chapter 2 a description of airExodus architecture and validation experiments will be presented. In addition, other simulators and some works about human behaviour in panic situations will be discussed. In chapter 3 a general overview of BitBang framework is initially presented, followed by a discussion about the EvacSafeX architecture and components already explored. Also, it will be presented some obstacles identified when defining the architecture and corresponded decisions to overcome them. The chapter 4 starts by a discussion of some experiments conducted with the purpose of understand some core components included in the purposed model. In this way, several personal attributes and individual's behaviour are investigated. Then, two different real certification scenarios are considered and compared to airExodus predictions. Finally, the chapter 5 presents some general conclusions of the proposed model and the obtained results.

Chapter 2

State of the Art

In this chapter, a presentation of the main concepts related to this work will be performed, being followed by a discussion on some evacuation simulators proposed during the last years. As already referred, this work has airExodus simulator as the major reference, wherefore a particular focus will be made. Finally, some references to human behaviour in evacuation and panic scenarios will be made.

2.1 Core Concepts

In this section, a brief reference to the core concepts underlying this work will be presented. Concepts like agent-based systems, complex systems and emergence of complex behaviour will be focused.

2.1.1 Complex Systems

The notion of complexity is usually applied to a wide range of contexts and many times in a subjective manner. Definitely, a definition of complex system has not already reached a consensus in the community [13–16] . However, a complex system can be defined as one composed by several individual elements that interact, resulting in an emergence of complex proprieties not derived from each individual components.

A complex system can be characterized by its hierarchical structure inasmuch as a set of very simple components interacting, forming higher level structures. These different hierarchical layers can be defined as levels of complexity. However, complexity is not only related to a result of a system composed of many parts but also to complex behaviour.

Another important aspect associated with complex systems is self-organization [16] . Whenever a new phenomena or behaviour is observed without any centralized control or external enforcing, the system is classified as being self-organized. Several examples of self-organization are presented in biology, in the traffic, in chemistry or in the society [17, 18] .

In this work, complexity is associated to an effort of defining a set of passengers with some individual attributes and capabilities in such a way that more complex behaviour emerges (without any centralized control), representing an approximation to the real world evacuation scenarios.

2.1.2 Agent-based systems

An agent-based system can be defined as a system such that several intelligent agents are interacting or communicating. A definition proposed by Wooldridge [19] identifies four main proprieties: autonomy, reactivity, pro-activity and social-ability. Autonomy is related to the fact that an agent is capable of taking independent actions. An agent is reactive given that it reacts to changes in the environment. They are also able to generate and attempt to achieve goals. Finally, they can interact among them changing information, negotiating or cooperating.

Agent-based simulations provide some unique advantages [20, 21]. First, every agent is able to have their own goals independently of the remaining entities. In this specific case, different passengers can easily have different evacuation exits to seek. Also, agent-based systems naturally support modeling complex interactions. For example, during an evacuation process, a passenger can stop so that another passenger can enter the aisle. Finally, agent-based systems can be parallelized in a easier way providing a better performance to the simulator.

2.2 airEXODUS simulator

In this section, a general overview of airEXODUS architecture an its core components is presented. Then, some of the most important validation experiments applied on the airEXODUS model will be discussed.

2.2.1 General Overview

airEXODUS [11] is a software designed to simulate evacuation scenarios in an aircraft structure, being used for aviation requirements certification, accident investigation, crew training and others. It was presented by E. R. Galea et. al. in 1989. It is an application of EXODUS agent-based simulator [22–24] in the field of aircraft evacuation scenarios.

A set of six core components - aircraft configuration specification, aircraft environmental specification, crew behaviour, passenger population distribution, passenger behaviour and passenger exit selection - are considered essential in computer simulation for aircraft evacuation certification [10]. These components are suggested to be defined and tuned accordingly to real data collected in certification trials (e.g. evacuation time tracking, video recordings).

AirExodus takes into consideration people-people, people-fire and people-structure interactions. The core structure is composed of five sub-models [25, 26]: the occupant, movement, behaviour, toxicity and hazard sub-models. Figure 2.1 shows airExodus sub-models and interactions between them.

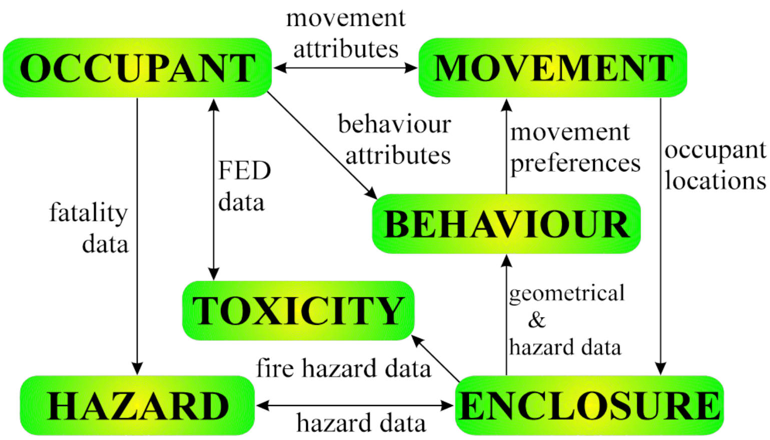


Figure 2.1: airExodus submodel interactions [1]

These sub-models are controlled by a rule-based system, being established a set of interactions between them. The spatial dimension is defined by a 2D grid where aircraft structural components and agents are placed in each grid cell. A graph is associated to a grid space where movement is restricted to a set of nodes connected between them. So, each agent is placed in a given node and can be moved to another node in each simulation step. Each node stores the distance to the nearest exit as well as information about how difficult is it to overcome it. Edges have an associated weight corresponding to the real distance between the connected nodes. Multiple floors are supported connecting them with stairs.

The user is able to build a new aircraft layout through a graphic interface where nodes and edges can be combined to design the enclosure. Therefore, the user is responsible for placing a set of objects and creating the navigation space according to his preferences, trying to represent a real aircraft cabin. Probably the most important part of the simulator is the clock. This is the master control of the model where passengers' decisions and world changes occur in each clock tick.

2.2.1.1 The occupant Submodel

Distribution of passengers in the aircraft is controlled by a sub-model population which supports different characteristics of each group. airExodus contemplates a collection of 20+ attributes which can be separated into different categories: physical (agility, gender, travel speed etc), psychological (patience, drive etc), positional (distance traveled etc), and hazard effects (FIN, FIH etc). Some of these attributes are static along the simulation while others change according to environment dynamics.

A special type of passenger as a way to represent crew members in the aircraft is also taken into account. Crew members have associated some additional attributes such as range of effectiveness of vocal commands, assertiveness at using voice commands and when physically handling passengers and their visual access to certain zones of the aircraft cabin [26] .

2.2.1.2 Hazard Submodel

This submodel allows the user to change the whole environment dynamics and its influence in the simulation progress. This encompass aspects like the fire gases spreading, smoke and heat. Along the simulation time, spatial position of these components can be dynamic - head height or knee height - and consequently influence passengers' behaviour in different ways. Additionally, the model has the capability of receiving experimental data collected in real world scenarios to produce different dynamics in the aircraft components.

2.2.1.3 Toxicity Submodel

The toxicity model determines the effects of hazard behaviour when passengers are exposed to it. Therefore, there is a strong connection between hazard and movement sub-models in the sense that physical and locomotion attributes are affected by the first one. For example, travel speed can be modified by the exposure to the narcotic gas released during fire propagation. Consequently, passengers can act according to environment conditions and start crawling as a way of avoiding the inhalation of toxic gases. Also, an implementation of Fractional Effective Dose from Purser's functions is used in the toxicity model and determines the effects of passengers' exposition to the narcotic substances.

2.2.1.4 Movement Submodel

Physical movement of passengers along the aircraft is controlled by Movement sub-model. This is responsible for determining the appropriate travel speed according to the passengers' perceptions about the surrounded environment. Also, once each node has an obstacle value associated, this sub-model decides whether passenger's agility is enough to travel over that node. However, the movement direction is not controlled by this component, being manipulated by the Behaviour sub-model.

2.2.1.5 Behaviour Submodel

Behaviour sub-model defines the passenger's response to each situation and consequently determines the most likely action when facing a given situation. Two different behavioural levels are distinguished in the model: global and local. The first one is related to the evacuation strategy responsible for moving an agent to his familiar/nearest exit. The second one is responsible for changing the global behaviour taking into account the occupant's initial response, negotiation with other agents and time associated with those processes.

Still regarding to local behaviour, situations such as initial response of passengers to the evacuation call, overtaking, conflict resolution and selection of alternative route are manipulated in this sub-model. For that purpose, the resultant behaviour is determined by a combination of the passengers attributes and a set of decision rules with stochastic roots.

Two different behaviour modes can be chosen by the user: normal or extreme. The first one assumes an orderly behaviour along the simulation following the global behaviour rules (normally used in the 90 second certification trials). In contrast, under extreme behaviour, passengers are more likely to choose actions such as moving away from the assigned exit, jumping over seats and choosing a farther exit instead of the closest one. This kind of behaviour reflects real evacuation scenarios in a more realistic way. Some of the local behaviours considered in airExodus are presented next.

Conflict resolution is probably the most complex local behaviour [1]. Generally, this kind of problems arise when passengers move from their seat to the aisle and several passengers are trying to reach the same space at the same time. For that purpose, this kind of conflicts is resolved according to a psychological attribute called *drive*. This is a measure of the assertiveness of a passenger. In fewer words, whenever the travel distances and speeds associated with each of the conflicting occupants are such that is not possible to determine which one can advance, then *drive* attributes of each passenger are compared and responsible for the final decision.

Another common behaviour is related to situations in which a passenger is being blocked by another with a lower travel speed. In this case, the occupant tries to find another alternative in the same direction. As last resort, airExodus also considers the possibility of jumping over an obstacle in order to overpass a bottleneck situation.

Regarding to behaviour near an evacuation exit, two factors are identified as being crucial [1]. One of them is the exit width due that it determines the number of passengers that are handled by the exit simultaneously. The other corresponds to the delay that each passenger is likely to experience when passing through the exit. This inhibition can be controlled by the user through the use of experimental data from real simulations. Both exit width and delay of each passenger are strongly connected and considered, since some deadlocks can occur when exit width is not big enough to support several passengers at the same time. This kind of behaviour is referred as being influent in the total evacuation time.

Later on, a different decision-making capability was proposed enabling occupants to determine the most favoured route based on environmental, physical and psychological information. Also, physical and emotional linkage between passengers is mentioned as an influence factor in the evacuation process [11]. For example, a parent and his baby are connected in the sense that the parent will hold him during the evacuation. This obviously affects the travel speed and agility of passengers.

2.2.2 Validation

Along the last years, airEXODUS has been object to several validation experiments. This process is crucial when designing and implementing a new simulator prototype. For that purpose, several indicators were defined as crucial to the simulation process. These parameters will be discussed in the following section.

2.2.2.1 Relevant Parameters

The relevant parameters defined in airExodus [27] are: Total Evacuation Time (TET), Personal Evacuation Time (PET), Cumulative Wait Time (CWT), Exit Ready Time, Passenger Exit Delay Time and Off Time.

The Total Evacuation Time corresponds to the evacuation time of the aircraft. It starts in the beginning of the simulation until the last passenger exits the aircraft. Therefore, a single measure is transversal to each simulation. The Off Time is associated to each passenger and represents the time required by a passenger to reach the ground once they have mounted the slide.

The Personal Exit Time is associated to each passenger and measures the time required for an occupant to exit the aircraft. Cumulative Wait Time indicates the total amount of time spent in a congestion, starting after the passenger has completed his initial response to when he has exited the aircraft. Exit Ready Time corresponds to the amount of time necessary to turn an evacuation exit available.

2.2.2.2 Validation Cases

The validation process is essential to show the simulator's credibility while representing a real world phenomena. Human behaviour representation, movement representation and metrics associated to evacuation performance are examples of simulation components whose validation is essential.

The initial implementation of airExodus considered a simplified approach about agents' behaviour. Decision-making process was restricted to a simple seeking for the nearest assigned exit without any route recalculation when passengers faced hostile situations. This means that every agent has a global information (indicated by the potencial associated to each navigation node) about the location and condition of the aircraft exits, resulting in a lower boundarie of the expected evacuation time.

The preliminary validation tests [11] resorted to Cranfield Trident Three real simulations considering different passengers characteristics and following the protocol of 90 seconds certification. The population was defined according to the standard mix population specified in the 90 seconds experiments with a different travel speed associated to each group of individuals, influenced by the gender and age.

The results of these simulations showed that passengers in the aisle seats reached the minimum evacuation time while the windows passengers in the windows seats achieved the maximum personal evacuation time. This result matches a real simulation scenario.

Also, the passengers' characteristics were assumed without following any pattern observed in real world situations having been generated for demonstration purposes. A set of different experiments under non-hostile environmental conditions were conducted considering a variable amount of available exit doors. Additionally, a different potencial associated to each door was considered in order to simulate the influence of crew members in the evacuation process.

Regarding to hostil environmental conditions, a severest conditions epicentre was considered in the rear of the aircraft, gradually spreading to the front. The fire hazard data incorporated in these simulations was artificial in the sense that only single layer values were considered and every hazard zone was well-defined as a block. Consequently, the location and nature of the resulting fatalities are affected by this simplicity. Ideally, data derived from real situations or generated by models is advised by the authors to achieve better results. Some faults in the hazard model were referred due to an absence of thermal effects caused by humid air [25].

Another interesting aspect presented in the *airExodus* simulator is related to the influence of cabin crew in the evacuation process [27]. Aircraft evacuation performance is referred as highly dependent upon the behaviour of cabin crew [28]. Initially, cabin crew was not implemented explicitly in the simulator being produced through various effects. These effects were classified into Passenger Exit Selection and Performance. The first one incorporated actions where cabin crew redirected the passengers to an exit different than the nearest one, increasing the distance traveled by each passenger. Cabin crew members are then taught to make an equally distribution of passengers along the available evacuation exits avoiding potential bottlenecks in evacuation exits. The second one is based on the influence of crew members' assertiveness in the passengers performance during evacuation by persuading passengers to follow crew members instructions. This is implicitly represented through a variation on the passenger exit delay time distribution. These aspects can be tuned resorting to data from real evacuation oservations and human behaviour associated to them.

Later on, a new algorithm to represent crew-passengers interactions was proposed and incorporated in airExodus [29]. This new approach considered the visual access (presence of smoke and its influence in vision capability) for crew and passengers, communication between them and a more robust crew decision process. Crew members firstly concern about whether a redirection is needed or not, followed by a selection of passengers to be redirected and the corresponding selection of the new exit to be considered. Consequently, an error related to that decision is associated. Finally, passengers can have different behaviours despite the cabin crew recommendation (e.g. in certification scenarios they are more predisposed to follow crew recommendations).

2.2.2.3 Validation with certification trial data

With the purpose of evaluating the simulator's accuracy when representing these specific scenarios, a validation using past wide body certification data was conducted by E. R. Galea et. al. [3]. More concretely, four wide body aircrafts were considered, having been observed a set of successfully predictions of previous 90-second certification demonstrations. Also, while each real certification trial is executed only once, computer simulations can be repeated several times presenting distributions of results instead of a single result. Real certification process (with a single evacuation trial) was evaluated as unable to meaningfully rank aircraft performance due to the probabilistic nature of evacuation process.

In another way, airExodus simulator was also used to analyse exit separation influence during evacuation [22] . For this purpose, certification conditions were assumed regarding to the passengers' behaviour. Throughout these experiments, they concluded that a separation between 60 to 170 feet has no significant influence in the total evacuation time. Therefore, computer simulation was pointed as useful not only for certification purposes but also to evaluate the impact of aircraft cabin aspects in the evacuation performance.

A more recent work, added an additional number of validation tests to airExodus simulator [3]. These tests have shown that airExodus is capable of successfully reproducing evacuation scenarios under certification conditions. Also, the model is pointed as able to reliably predict the evacuation process during its execution.

2.3 Other evacuation agent-based simulators

Along the last years, other agent-based simulators have been presented and discussed. Some of them make use of global navigation algorithms where space is discretised onto navigation meshes [30] or roadmaps [31]. A set of global pathfinding algorithms (e.g A*) are then applied to plan an optimal route towards a goal while avoiding collision with a static environment.

Otherwise, once global navigation considers a static environment, a local navigation algorithm can be more adequate when dynamic entities (e.g. agents) are placed in the simulation world. In some cases, local navigation algorithms are responsible for adapting agent's velocity while moving towards a location previously defined by a global navigation algorithm. This class of algorithms is known as "collision avoidance" or "steering" algorithms [32].

Many have also created a relationship between particle motions and crowd movement. An example is the panic simulator built by Helbing et al. [33, 34] . However, some studies indicated that crowd behaviours do not follow the physics laws since that humans are capable to make their own choices (e.g. direction and velocity). This kind of approach is also considered contradictory when compared to some observed crowd behaviours, such as herding behaviour and multi-directional flow.

Other simulators follow a matrix-based approach. In these systems the environment is discretize into cells where each one corresponds to an empty space, an obstacle, a place occupied by an individual or regions with some environmental attributes associated. Therefore, individuals are able to move to surrounding cells based on the current state of the neighbourhood. Some examples of matrix-based systems are Pedroute [35] and Egress [36] which have been used in building evacuation simulations. Some problems can be pointed out in matrix-based systems when compared to real observations and modelling crowd flow [37].

2.3.1 Ped-Air

In the evacuation field, a Andrew Best et al. work resulted in an agent-based simulator called Ped-Air [21], built on the Menge crowd simulation framework. A Behavioural Finite State machine was used to represent the mental state of agents along the simulation. In contrast to the airExodus framework, Ped-air didn't focus only on the evacuation process but also on loading and unloading of passengers.

Behaviour model was defined through a set of possible behaviours (states) and events (transitions). This encompasses situations like waiting, aisle obstruction, physiological alternations, evacuation stress, and others.

Navigation is defined by a navigation mesh responsible for supporting global navigation algorithms. Regarding to the local navigation algorithms, both a social-force-based model and a velocity-space model were explored. The first one suffered from deadlocks when unloading the aircraft consisted in obstacles forces that caused oscillations in the narrow rows. The second one is related to the situations in which two agents arrive at the aisle from opposite rows causing an indefinite wait of both agents across the aisle.

To tackle these kind of situations and avoid deadlocks, the symmetry breaking algorithm was used. This mechanism captures asymmetric relationships between the agents and assigns priorities to each agent in order to solve these situations.

However, a restricted amount of passengers' behaviours and categories was considered in the simulator. For example, groups, children and passengers with physical disabilities were not considered.

2.3.2 MASSEgress

MASSEgress framework was proposed by Xiao Pan et. al. [38] and modeled considering each agent as an autonomous entity. Each one interacts with the environment and other individuals according to an individual behaviour model and a set of crowd interaction rules, respectively. Also, a "perception-action" approach was adopted to represent human cognitive processes which main purpose is an observation of some "chaotic" dynamics and emergent phenomena. Decision process is controlled by a set of decision rules that are triggered according to the perceptions received from agents' sensors.

Every agent's movements are performed in a continuous space where both direction and velocity are defined by some steering behaviours. Therefore, agents are able to walk randomly around the environment, detect obstacles and avoid them, seek for a given target, negotiate with other agents exchanging information and reaching agreements, and follow a given dynamic target.

Despite the simulations presented by the authors have not considered an aircraft environment, some results indicates an emergence of interesting phenomena during building evacuations. Additionally, other human behaviours in panic situations such as pushing and knocking are suggested, in spite of not being implemented in the proposed framework.

2.4 Human Behaviour in Panic Situations

The understanding of human behaviour and crowd behaviour is essential when designing a new computational simulation framework. Therefore, along the last years some ideas on this thematic have arised.

A human decision-making process was explored during MassEgress implementation [38], identifying the instinct, experience and bounded rationality as the three core classes of human behaviour. Humans take instinct actions (e.g. fear, death, survival and pushing others) without following a conscious mental process. Experience is also an influenciating factor due to the fact that humans tend to follow familiar pathways in panic situations. Finally, bounded rationality corresponds to a decision process responsible for selecting the available possibilities, weighting them according to the associated consequences and choosing the most favorable. This process is classified as bounded given that neither all options nor all consequences are considered and available during the decision stage.

Social behaviour has a major importance in panic situations being a field of many researches. The social identity of each individual and the personal space (different among different cultures and social roles) were identified as major keys in these scenarios [39]. Social and cultural differences among individuals can make individuals act anti-socially. Pshysical space between them is also an important aspect given that when perceiving a lost of personal space, an urgent need to move appears. Consequently, disruptive behaviours within crowds can be observed and chaotic scenarios can emerge [37].

Also, individuals are normally affected by their uncertainty about a given situation [38, 40]. When a novel situation is perceived they are more likely to follow the actions of others, such as in hearing behaviour - under stress and uncertainty situation there is a tendency to follow others.

Another important aspect is related to a social inhibition and its influence in the evacuation process. The initial reactors (usually cabin crew members) in a emergency situation play a key role in crowd behaviour [38]. If crew members happen to be behaving chaotically, the remaining individuals will instinctivly perceive it as if there is something wrong, triggering anxiety and stress reactions.

In an attempt to understand the most influential psychological and physical attributes in panic situations, a research with the purpose of converting these abstract ideias into concrete ones (and useable data) was conducted by Neal S. Latman et. al. [41]. For this purpose, a questionnaire was developed and given to the individuals prior to their participation in the simulated emergency evacuations of aircraft cabins. As result of these experiments, they observed that only 3% of the individuals indicated that cabin crew hindered them during the evacuation and 37% reported that fellow passengers hindered their evacuation. Also, some passengers indicated that the evacuation process was more difficult under competitive conditions than when a cooperative behaviour was perceived. Generally, the passengers considered that the most frustrating moments occured when waiting in the aisle.

An interest observation referred in Neal S. Latman et. al. work is related to the seat climbing behaviour of some passengers. Some of them reported that this kind of behaviour spread a feeling of frustration among the remaining passengers and had a negative impact in the evacuation performance. Finally, psychological attributes such as anxiety, insecurity, decisiveness, assertiveness and leadership were pointed as crucial in the passengers' decision process.

2.4.1 Aircraft Evacuation

In an effort to study the most frequent behaviour observed in both evacuation certification scenarios and real accidents, some works were conducted in the last decades. Aspects like passenger choosing rule for the evacuation exit and decisions taken when facing congestion, played a major role in the presented work.

Generally, passengers are susceptible to choose the nearest exit both when they know the available exit as well as there is no information about their location. However, when there is no information about the available exits, the occurrence of behaviour such as follow masses or avoid them, increase. Also, there is a trend to move toward the forward direction of the aircraft.

When faced a congestion scenario, different behaviour can be observed depending on the knowledge about the corresponded exit's availability. In both cases, a rerouting is observed when the passengers have knowledge of other exits' availability. Even when they have no information about other exits, they are susceptible to change their route and find another evacuation exit.

Another interesting point is related to the influence of panic in the passengers' behaviour. In the case of fail to evacuate for a long time, an increase of panic is observed in each passenger. A high degree of uncertainly is generally observed when panic increases and there is a trend to follow the masses or find other exit in an independent manner. Panic is associated to an emergence of chaotic behaviour and a spread of this feeling among passengers is observed. Therefore, the panic degree of a passenger has an high influence of the other passengers around them.

Chapter 3

Architecture

Along this chapter both EvacSafeX conceptual model and architecture will be presented. The proposed model prototype was developed resorting to a framework developed by Tiago Baptista et. al. [2, 42, 43] called *BitBang*. Therefore, a brief presentation on this framework will be performed at the beginning of this chapter. In a second part, the main components of the proposed model are described as well as their relationships with *BitBang* framework.

3.1 BitBang Framework

Bitbang framework has roots in the Artificial Life systems and Complexity Science wherefore the simulated world is composed by a set of entities. These entities can be either inanimate objects designated as *things*, or entities with capabilities of perceiving and affecting the surrounding environment. These are called *agents*. Both have attributes that characterize them - *features*. Agents are able to communicate with the environment using *perceptions* (to gather information) and *actions* (to change environment or their own behaviour), taking decisions using the *brain*.

The framework is composed of two separated software components: the BitBang Core and the BitBang Simulation Engine. The first one implements the components of the conceptual model while the second one integrates a three-dimensional graphics engine and a physics engine in the conceptual model. Figure 3.1 shows an overview of BitBang components and relations between them.

Most of the classes in the BitBang Core are abstract since they are designed to be implemented in specific cases of perceptions, features, brains, objects and worlds. Some

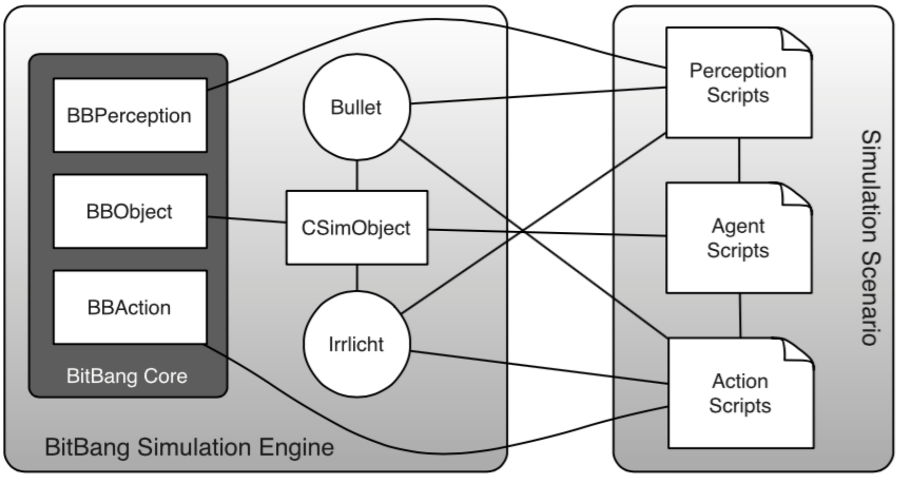


FIGURE 3.1: Global architecture diagram of the BitBang framework [2]

of these entities are already implemented in the framework and can be easily used. Next, a brief description of some of these entities is presented.

A *perception* holds a specific type of data (number, boolean or string), having a set of operators associated to each type. Some of these perceptions are abstract and can be specified for a given purpose, while others have a final implementation and can be used directly.

In contrast to perceptions, a specific set of specific *actions* is not provided by the framework since all of them are problem dependent and highly correlated with the characteristics of the agents and surrounding world. BitBang implements two different abstract types of actions: atomic and continuous. The atomic actions are executed whenever triggered by the brain and correspond to a single operation. On the other hand, continuous actions are triggered by the brain and executed until a specific stop condition is activated.

Another important entity is *feature*. It corresponds to characteristics of a passenger or any other object. It can be, for example, 3D form, colour, or anything else that characterizes an object in the model. Similarly to perceptions, the features have a type associated to them (number, string or boolean). A passenger can also perceive features about himself.

Finally, the *brain* is responsible for defining the agent's local behaviour through a list of rules, dealing with the perceptions gathered from the environment and choosing the most likely action. Although BitBang's brain is totally independent from the algorithm chosen for the decision process, a *rule list* algorithm is already incorporated and will be adopted in the model proposed in this work. This approach has the advantage of allowing a direct inspection of the agent's brain.

The *Rule List Brain* is then composed of an ordered list of rules in which each rule is composed of a conjunction of conditions and a consequent action. In every "thinking" process, these rules are evaluated according to the specified order, being selected the first rule in which every condition is true. Then, the corresponding action is executed. For better understanding this process, a syntax grammar of rule list brain is presented in Figure 3.2.

```
1.  <rule> ::= IF <condition-list> THEN <action>
2.  <condition-list> ::= <condition>
3.  <condition-list> ::= <condition> AND <condition-list>
4.  <condition> ::= <perception> <operator> <perception>
5.  <condition> ::= <perception> <operator>
```

Figure 3.2: Syntax of the Rule List brain [2]

3.2 Model Description

In this section, a description of EvacSafeX model will be performed through a relationship between the core components of the proposed model and BitBang's architecture. Then, an overview of the aircraft components and how passengers' interaction with them develops is presented. Also, a discussion on agents' behaviour and its representation on the model is described. Agents' movement and collision detection/resolution are also discussed, being analyzed the decisions taken to reduce computational cost associated with this process.

3.2.1 Core Entities

As already referred, EvacSafeX was thought to be strongly connected to the BitBang's architecture. The concept of a system without any central control is a major key in this model. Therefore, many entities in this model extend components already contemplated in BitBang framework.

One of the most important entities are the *passengers*. They are definitely the agents of the entire simulation and interact in a proactive manner with the surrounding environment. Passengers are then an agent as defined in the BitBang framework. They are placed in a world and are able to perceive and act according to a set of abilities.

Similarly to BitBang's implementation, their decision-making process is controlled by a set of decision rules defined in their brain.

As already mentioned, flight attendants have a major role on the passengers' safety and actively influence the evacuation performance. Therefore, the proposed model considers an explicit representation of cabin crew during the simulation process. Similarly to passengers, an air hostess is represented as an agent in the simulation having associated a range of perceptions and actions controlled by a decison-making process defined by a rule list brain. These actions may also lead to some changes in their physical appearance and gestures, which can be perceived later on.

The world is defined by a set of objects that can be dynamic or static. The dynamic components can have different spatial locations during the simulation (e.g. passenger). On the other hand, the static objects are initially placed in a given location and their position remains unchanged. Although static components are not dynamic upon their position in the environment, they can have different dynamics. For example, an exit sign is static with respect to its position during the simulation. However, it can be enabled or disabled, having a consequent influence on passengers' perception.

Regarding to the aircraft components considered in the model, the following ones can be highlighted: seat, obstacle, exit sign and evacuation exit. A brief description of these components is presented next.

A *seat* corresponds to a place where a passenger starts his evacuation process. For performance reasons, a seat is not represented as a single object in the aircraft. Instead, a block of seats is defined with a given number of rows and seats per row. Therefore, an aircraft can be composed of several seat blocks that combined will result in aisles represented by the free space between two blocks side by side. This way of representing seats is considered flexible to design any structure of aircraft cabin. In addition, a very simple rigid structure defined by its size can be placed in the environment to represent an obstacle. These obstacles can represent walls or any other unsurpassable objects.

Evacuation exits are a very important component in this model since that evacuation process is highly dependent on their physical and functional properties. This is not new as it was already referred in chapter 2. An evacuation exit is defined by its side position (left or right), its location along the aircraft length and its dimensions. Therefore, different dynamics in the evacuation performance are expected to be observed when modified these properties in the aircraft layout.

Other components also considered in the aircraft structure are the *exit signs*. In fact, a major influence is associated to them due to their role in assisting passengers to locate exits, specially in darkness conditions. Despite the fact that this component is not explicitly represented in airExodus, it is incorporated in EvacSafeX. These signs are placed in a fixed position but can change their state according to aircraft control system. They can be activated or deactivated. In the first case, they can be perceived by the passengers, guiding them along the evacuation process and suggesting a recommended evacuation exit. In the second case, they cannot be perceived by passengers, providing no information on evacuation exits' location.

As already referred, spacial dimension of EvacSafeX is defined by a set of aircraft components such as seat blocks, obstacles, evacuations exits, etc. These components are placed by the user in order to compose an aircraft enclosure layout. In the current version of the prototype, components are referenced in a configuration file as well as their corresponding attributes (position, dimension etc). However, all these aspects were already thought to be further manipulated with an interactive graphical interface.

In a general overview, Figure 3.3 presents a global class diagram of the components that make up the EvacSafeX model.

3.2.1.1 Movement Graph

Although both aircraft components' coordinates and passengers' movement are being considered in a continuous space, the resulting movement is restricted to a space confined to a graph. A collision verification/avoiding algorithm applied in continuous space with so many objects could suffer some performance issues [44]. So, a graph structure avoids a collisions' verification of passengers against objects with a static position in the aircraft cabin. Also, *airExodus* experiments have demonstrated that an aircraft space can be discretized without a significant loss of space representation. Effectively, an aircraft enclosure layout is generally composed of well-defined structures and zones.

Furthermore, it was decided to use a graph structure instead of a matrix-based approach, once in this way a higher degree of freedom is given to agents' movement. With a matrix-based approach, each agent must be placed in a grid cell and be moved sequentially to the neighbourhood. On the contrary, the proposed navigation structure allows a better representation of human movement, through an application of some path-finding and steering behavior algorithms in a continuous space defined by graph's paths.

One hypothetical problem identified in *airExodus* model is the graph building method. As already referred in this work, *airExodus* provides a graphical interface where users are able to define an aircraft structure as well as the zones allowed for passengers' circulation. These zones are then defined by nodes spaced within a pre-determined distance and connected according to a criterion defined by the user. As expected, a

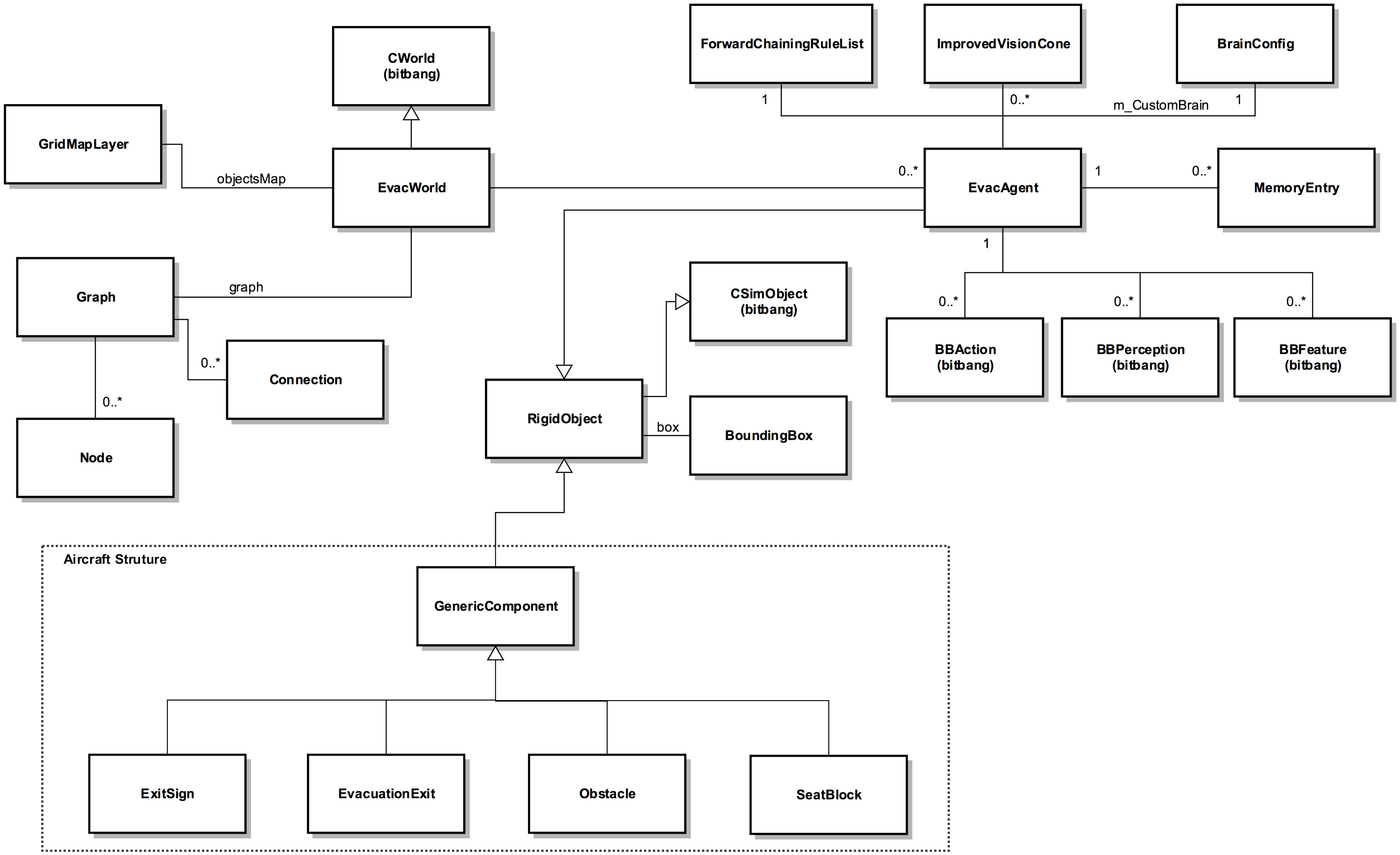


FIGURE 3.3: General overview of the components considered in the EvacSafeX prototype.

heavy workload is associated to this process as the user needs to interactively build a graph structure.

To tackle this problem, an automatic mechanism to build a graph of a previously defined aircraft cabin was included in this model. Therefore, after an user defines an aircraft layout (placing aircraft components along the aircraft enclosure), an autonomous algorithm defines a set of nodes and edges along the aircraft cabin following a procedure further detailed in this section.

An important aspect in this process is the distance between nodes. A node can be seen as a place where passengers can stay without being superimposed by any other object in the environment. So, two nodes must be placed at a distance greater than passengers' dimension in order to grant that a passenger is not sharing the same space of others at the same time. Also, a distance between each node and the static objects must be respected. This distance must be greater than half of the passengers' dimension ensuring that in a given node, passengers are not overlapping any other object.

Given that each passenger is placed in a seat when started the evacuation process, a graph node is positioned in front of each seat. Consequently, nodes belonging to the same seat block row are connected. To assure the distance rules already referred, the distance between the same point of any two consecutive seats in the same row must be greater than the passenger's dimension. In this way, one can assure that there aren't any overlapping passengers at the begging of the simulation. Figure 3.4 shows an example of a seat block composed of 2 rows and 3 seats per row.

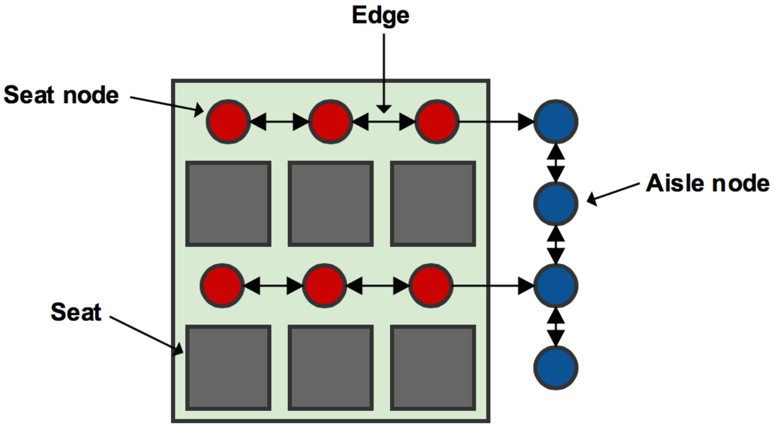


FIGURE 3.4: Movement graph structure

As can be also observed in Figure 3.4 , two types of different nodes are being considered - seat nodes and aisle nodes. Later on, it will become clear that this distinction is made because the passenger has sometimes to perceive whether they are inside a seat block zone or already in an aisle.

Another important aspect is related to connections between nodes. As seen in Figure 3.4 they are bidirectional when the corresponding nodes have the same type, in contrast to edges between seat and aisle nodes. This can be justified by a simplification of the occupants' behaviour during the simulation. Effectively, once moving along an aisle, passengers are not susceptible to return to a seat zone when these zones are only connected to one aisle. In these cases, passengers are only allowed to move between aisle nodes as soon as they leave their seat zone.

Evacuation exits are also explicitly represented in the graph. The number of nodes composing an exit depends on its width. Several passengers can be exiting through an exit at the same time if the exit's dimension supports both passengers. So this is controlled by a relationship between passenger dimension and evacuation exit size.

Regarding to connections between nodes, once they represent circulation zones, a verification of possible collisions with static objects is performed. Therefore, two nodes can only be linked if no collisions are detected when moving a passenger between those nodes (considering a movement in straight line). To complete the remaining aircraft area, a scanning is performed as a way of placing nodes in empty spaces and connecting them according to the rules presented before.

As stated before, although passengers' movement is restricted to the space defined by graph, their movement occurs in a continuous space. This means that an agent can be placed in an edge instead of only in a node. Effectively, this approach is different than the one considered in airExodus (see section 2.2). Therefore, a passenger moves along graph connections according to a velocity vector, being determined a new target node whenever reached a new node.

However, some changes in the passengers behaviour can occur while they are trespassing a given edge in the graph. Consequently, these changes can be associated to new perceptions and locations. This means that if a different brain rule is triggered implying a change of movement direction, a passenger can return to the start node instead of reaching the end node, and then calculate a new target node.

Agents' movement in the proposed model has an important component inspired by the steering behaviour concepts. In each simulation step, an agent is able to perceive the surrounding environment and adjust its speed in accordance with these perceptions. For example, an adjustment of its speed is performed whenever perceived an agent in a close area, giving the real notion of human's movement. Similarly, particular attention was given to scenarios in which an agent collides with other while trying to take a given movement step. Effectively, different simulation steps make it possible that distinct movement step sizes may be observed in each simulation frame. In these situations, the movement step size is adjusted in such a way that maximizes the space covered in that same simulation step. In this way, the influence of agents' movement in the total evacuation time when used simulation time steps can be minimized.

3.2.2 Conflict Resolution

One important aspect when dealing with multi-agent systems is conflict resolution. These kind of problems can emerge due to several passengers trying to move towards the same location. In this case, conflict occurs when more than two agents are moving towards the same node. Figure 3.5 illustrates a situation of conflict between three agents.

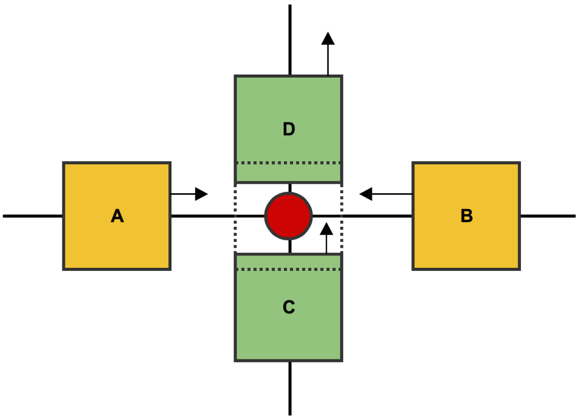


FIGURE 3.5: Representation of a conflict resolution scenario. Passengers A, B and C are moving towards the same node and both A and B need to wait until C leaves the conflict region.

In Figure 3.5 passengers A, B and C are moving towards the same node. In this situation, passenger C was the first one reaching the conflict region, consequently, both A and B will have to wait until that zone becomes free. As agents are processed sequentially by the simulator, the first one reaching conflict zone brings as a consequence the fact that all the other agents trying to move to the same zone will find themselves destined to wait.

However, there are some scenarios where conflict region should not be applied and multiple passengers should be able to share that region at the same time. According to many observations of crowd behaviour, whenever both agents are moving towards the same direction, an adjustment of their velocity vectors is observed in order to create a consistent/ordered queue. Observing Figure 3.5 , the agents C and D are both on critical zone once they are moving in the same direction. In this way, it is possible to avoid unjustifiable free spaces between passengers, allowing a realistic representation of crowd flow. In summary, this kind of behaviour can be seen as instinctive and then it is processed independently of the agent's brain rules.

However, in real evacuation scenarios some human psychological attributes take a major influence on this kind of situations [40]. For example, a passenger walking along an aisle can wait in order to let others enter into the aisle. Furthermore, some personally selfish behaviours can occur (e.g. push or kick others) in reactive way and situations as described in Figure 3.5 can have different outcomes. Therefore, these kind of aspects are taken into account when dealing with conflict resolution situations.

As discussed in section 2.4, certification demonstrations are characterized by a high cooperative component between the passengers. Effectively, in conflict scenarios (e.g. entry to the aisle) altruistic behaviour takes a major role. Therefore, the proposed model takes a particular focus on this kind of scenarios. Negotiation between passengers is incorporated through some specific perceptions and actions that can be used in the passenger's brain, as will be detailed in sections 3.2.4.2 and 3.2.4.3.

3.2.3 Collisions Grid Map

As already discussed (see section 3.2.1.1), agents' movement is delimited by a graph responsible for delineating the zones in which circulations is allowed. However, this graph only takes into account the static objects in the simulation world in a way that collisions avoidance against dynamic objects (e.g. passengers) is not guaranteed by it.

A naive approach could involve a collision verification considering every agent in the aircraft structure. As expected, this could give rise to several problems related to the simulator's computational performance, and an alternative approach was explored. Thus, a new support layer was considered with the purpose of dividing the aircraft cabin into a grid map where each grid cell corresponds to a given zone [45].

Each grid cell holds a map with references to every object which is totally or partially contained in that cell. Therefore, when a collision verification is performed, only the dynamic objects partially or totally inside the same cells are verified. A significant decrease of the number of agents considered in the collision verification is reached. Therefore, these structures need to be updated whenever an agent moves towards a new position.

There are two aspects with a major influence on the spatial grid layer performance: the cell and the objects' size. Whenever the cell size is too small when compared to object's size, a verification of a large amount of cells is needed. Consequently, the computational cost associated to this process increases. In addition, if there are entities that vary greatly in size, an appropriate cell size cannot be found.

In this model, once every passengers has about the same size, a spatial grid layer is a good approach to reduce the computational cost associated with collision detection. For a better understanding, Figure 3.6 presents an example of a grid map layer used in the EvacSafeX.

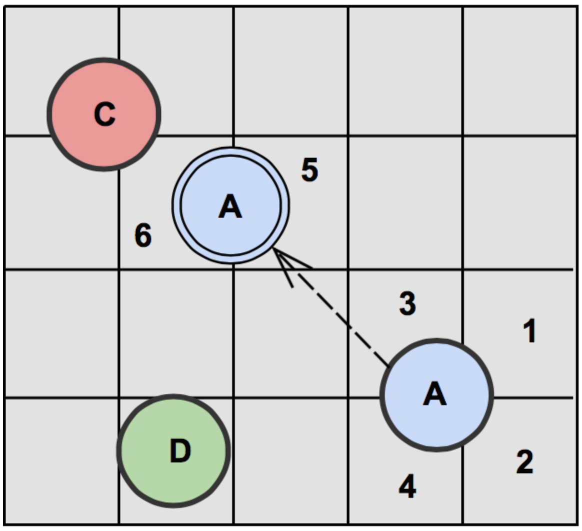


Figure 3.6: Representation of grid map layer usage in collision verification scenario

By looking at Figure 3.6 it is possible to verify passenger A moving along the velocity vector represented by a dashed directional arrow. Initially, cells 1, 2, 3 and 4 contained references to passenger A. However, when passenger A tries to move to the new position, only objects referenced by cells 5 and 6 are considered in the collision verification. So, agent C is the only one which is considered in collision verification due to being the only one who has cells in common with passenger A. Given that a collision is not verified, then passenger A moves to the new position and cells 1,2,3,4,5 and 6 are updated.

3.2.4 Agent's Proprieties

Agents in the entire simulation are associated to a given population group, sharing similar psychological and physical attributes. Also, they are able to perceive and change the surrounding world, as well as their personal state. Some of their actions are defined internally and influenced by stochastic attributes, while others can be explicitly modified in the agents' brain. In a general manner, the proposed model seeks to provide a high degree of freedom when designing passenger's behaviour and personal attributes.

Another important aspect is the *memory*. Despite the fact that an explicit implementation of agent's memory is not provided by *BitBang* framework, a memory mechanism was included in the *EvacSafeX* architecture. So, a given perception can be recorded in the agent's memory and be perceived to take later decisions.

In summary, and correlating to BitBang's architecture, agents are defined as the following in the EvacSafeX architecture:

- **Features**: physical, psychological and other personal attributes
- **Memory**: information perceived and recorded
- **Perceptions**: external, internal and memory perceptions
- **Actions**: external and internal actions
- **Brain**: rule list

The following sections will describe each component of the agent's architecture as well as the mechanisms associated to each one.

3.2.4.1 Features

The *features* are mainly associated with both physical and psychological attributes of the agent. They are defined by their data type (e.g. number, string, boolean) and dynamics over the simulation. So, some of them are static along the simulation while others can change its state due to an external or internal factor. Figure 3.7 shows a class diagram of the features provided by the proposed model.

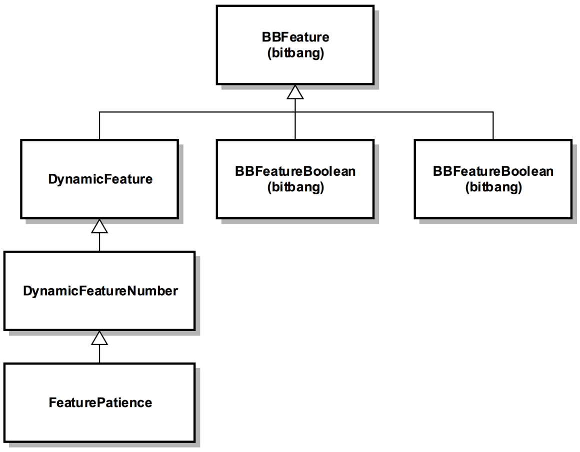


Figure 3.7: Features' organization and corresponded classes

As dynamic psychological components should be updated during the simulation, a particular type of features is included in the model. Dynamic features are distinguished by an "update" mechanism with the purpose of determining the corresponding value in each simulation step. Therefore, it possible to implement a certain model responsible for updating a given feature over the simulation process.

Patience

Whenever discussing human behaviour, an important aspect is the patience level of the individuals. In aircraft evacuation context, it plays a major role on their decisions, particularly when they are facing congestion scenarios. Patient individuals are more likely to wait in long queues instead of finding an alternative route. On the other hand, anxious subjects are persistently searching for alternative routes, as a way of increasing their evacuation effectiveness.

In this sense, the proposed model provides a dynamic feature that represents patience level of a given passenger. This is determined according to the average speed at a pre-defined time-window. So, a window size is specified with a given number of seconds pre-defined by the user. Therefore, it is possible to introduce new rule conditions in passengers' brain that are triggered according to the patience level at a given instant. Figure 3.1 shows a rule whose patient level takes an influence on its veracity.

```
IF istrue(See evacuation exit back) AND Agent direction back = 0 AND Feature
    ↪ Patience < 30 AND Random number < 80 AND Crowd density front > Crowd
    ↪ density back THEN Go to evacuation exit back
```

Listing 3.1: Example of how patience level can take influence in the agent's behaviour

The rule 3.1 indicates a redefinition of the target evacuation exit. However, this rerouting decision only takes place in cases where patience level reaches a given threshold. In this way, it is possible to represent real behaviour in which passengers are likely to re-select their target exits whenever perceived a low patience level.

Response Time

Before the evacuation call, each passenger is placed in their seat waiting for an order which indicates the beginning of the evacuation process. However, a period of time is associated from the moment in which the evacuation signal is given until a passenger responds to it. This passenger attribute is pre-defined before the simulation start, according to a given distribution.

Exit Delay Time

Whenever a passenger is close to an evacuation exit, there is a time spent to fit the body to the exit size and also hesitation before going onto the evacuation slide. Both these attributes are encapsulated in "Exit delay time" in order to model this critical moment. Similarly to other attributes, this is generated by a given probability distribution, initially pre-defined for each population type.

Walk Speed

Passengers have also associated a maximum locomotion speed. It corresponds to the speed when no obstacles or other influences are interfering with their speed. However, this only corresponds to a maximum speed, wherefore several internal or external perceptions can influence the travel speed of an individual.

Rotation Speed

Physical agility is many times associated to humans and has major influence on their decision. In the proposed model, this is represented by a rotation speed associated to each one. Effectively, it takes an influence in the vision cone position when performed drastic direction changes. Therefore, a passenger is progressively rotated towards its movement direction.

Is Crew Member

As already known, a special type of passengers is considered in aircraft evacuation scenarios. The crew members are responsible for helping every passenger during the evacuation process through their gestures and vocal commands. They are clearly characterized by their uniform which is represented as a feature which can be perceived by the other individuals in the simulation environment.

Panic

An important psychological component, often observed in evacuation contexts, is panic. Effectively, the panic state of the passengers plays a major role on the efficacy of the evacuation process. For this purpose, this feature is included in the propose and can be used to influence the passengers' decisions during the evacuation.

As presented in section 2.4, the panic degree of each passenger is generally influenced by the time pressure. So, an increase of the psychological state is observed over the evacuation time. Furthermore, each individual is also influenced by the panic degree of the neighbourhood. The higher the number of neighbours in state of panic, the greater the panic's degree of the individual. Therefore, this psychological feature is updated according to these both components.

Is Redirecting Passengers

Crew members are characterized by their gestures as a way of redirecting or improving the evacuation effectiveness of passengers. Therefore, this *boolean* feature indicates whether a crew member is currently performing a set of gestures with the purpose of calling/redirecting passengers to a given location.

3.2.4.2 Memory

Another component included is associated to the capacity of recording information collected from the environment and saving it in order to, later on, take decisions. Indeed, humans are often moving towards some locations that are not perceived at a given moment. Memory is effectively a major component in human's capabilities and should not be discarded when representing human behaviour.

Although the model supports different types of memory, a major importance was given to the one related to spacial locations. They can be considered the most predominant feature in which memory takes a major role in evacuation scenarios. Figure 3.8 describes how memory components are organized in the proposed model.

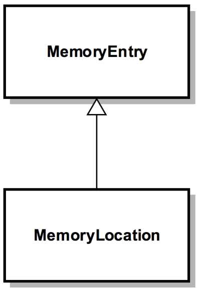


FIGURE 3.8: Class diagram of the agent's memory components

MemoryLocation entity has the purpose of recording a given location previously defined or perceived by the agent. Therefore, a specific set of perceptions are responsible for updating agent's memory as discussed in section 3.2.4.2.

Two different specific memory entries are already included in the model: *Most familiar exit* and *Nearest evacuation exit*. The first one corresponds to an exit previously associated to a given agent. It represents an exit memorized during pre-flight safety demonstration, or the boarding door. The second one corresponds to the nearest evacuation exit internally perceived by the agent. When started a simulation, this memory entry can be randomly assigned or pre-defined according to a given criteria (e.g. global nearest exit according to its initial location). Lately, it is updated according to the exits perceived during egress. Therefore, memory is updated whenever an exit is perceived with a distance smaller than the last one recorded in memory.

However, some empirical experiments suggested a distinction between the nearest exit in front of a passenger and the one located behind him. In this way, there were defined two distinct memory entries associated to the nearest exit, being updated according to a comparison between exit's direction and passenger's movement direction. Therefore, three different entries in memory are considered to represent the nearest exit in memory: *global nearest exit*, *nearest exit in front* and *nearest exit back*.

Finally, two other memory entries are considered in the proposed model. The first one corresponds to the movement direction of the last agent perceived through the frontal vision cone. With it, an agent is able to remember that direction and moving towards the corresponded location. The second one is related to the nearest crew member perceived by an agent. Effectively, some passengers can remember crew member's gestures, and take them into account to take later decisions.

3.2.4.3 Perceptions

Agents are able to perceive the surrounding environment through their own vision cone. This cone is defined by a vision range and an angle. Figure 3.9 shows an example of a vision cone associated to each agent.

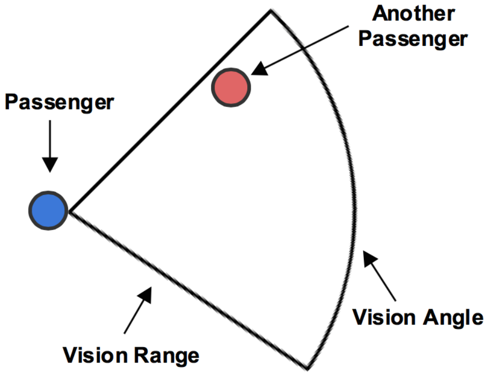


FIGURE 3.9: Agent's vision cone when perceiving other passengers in the environment.

As will be discussed in section 3.2.4.5, apart from the front vision cone (pointing in the agent's movement direction), each agent has also a back vision cone associated to him (pointing in the reverse direction of the agent's orientation). Therefore, distinct perceptions are considered in the model to distinguish between what is perceived by frontal or back vision cones. For convention, the name of the ones associated to back vision cone should end with the keyword "back".

In a general overview, all perceptions included in the model are presented in Figure 3.10.

Perceive Location

An important aspect to be considered is related to the scenarios in which an agent perceives a given object and desires to move toward its location. Effectively, this is

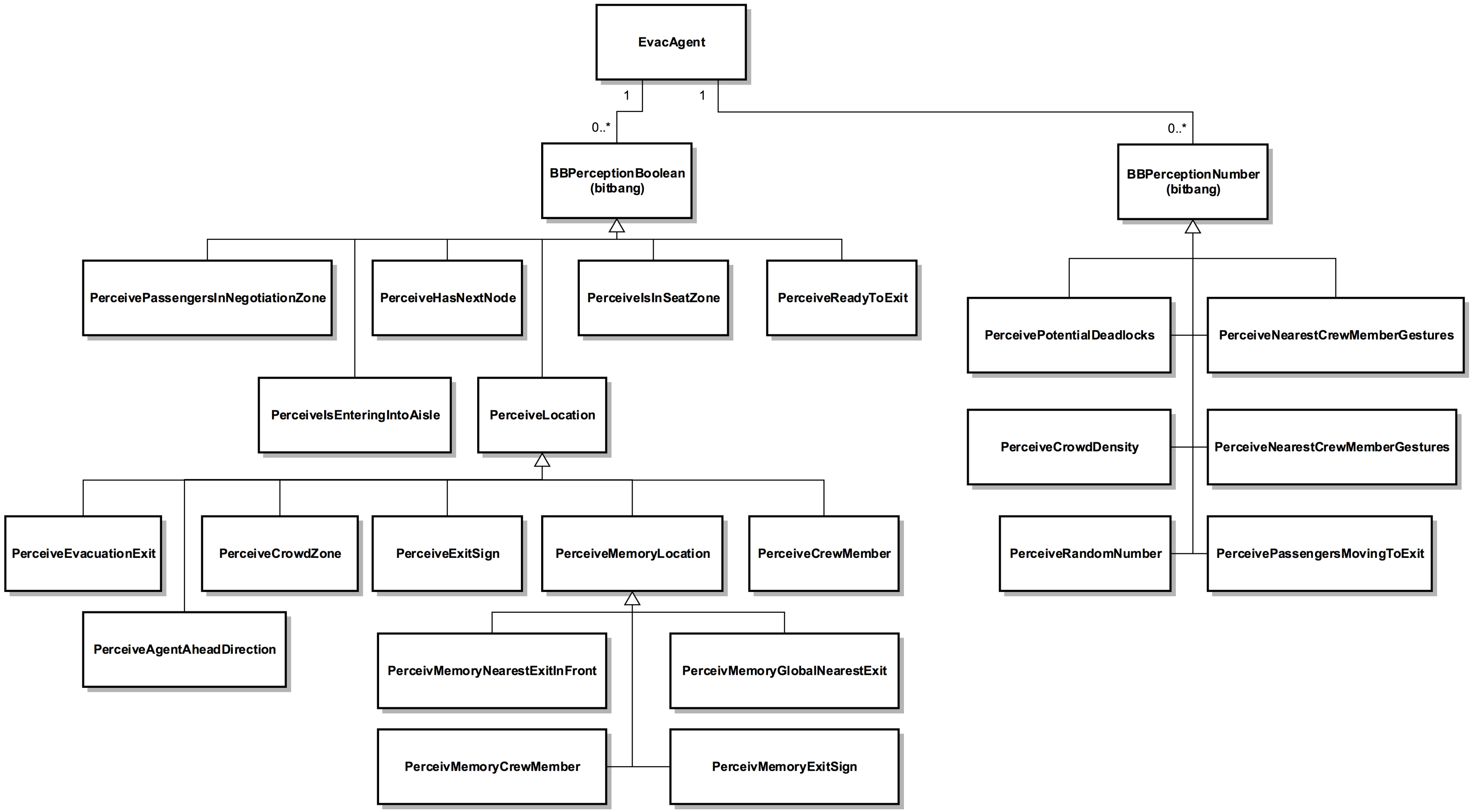


FIGURE 3.10: Architecture of the components associated to the agent's perceptions.

the most frequent behaviour in evacuation scenarios such as when an evacuation exit is perceived and the passenger starts moving towards its location. For this purpose, a particular perception class was considered as a way of supporting this kind of behaviour. Therefore, this is a *boolean* perception (as defined in *BitBang*) which value indicates whether a specific object is within the agent's field of view.

Apart from the boolean value, this kind of perception holds the location of the perceived object. Therefore, it can be used later on to take a specific action which resorts to the perceived location, as discussed in section 3.2.4.3. Following this mechanism, some similar perceptions were incorporated in the model and applied to specific scenarios (e.g. different objects), as presented in Table 3.1.

Name	**Class**	**Description**
See an evacuation exit	PerceiveEvacuationExit	Perceive the nearest evacuation exit in the field of view, if exists
See an exit sign	PerceiveExitSign	Perceive the nearest available exit sign in the field of view, if exists
See an agent ahead	PerceiveAgentAheadDirection	Perceive the movement direction of the nearest agent in the field of view, if exists
See a crowd zone	PerceiveCrowdZone	Perceive the most densely zone, if exists
See a crew member	PerceiveCrewMember	Perceive the nearest crew member, if exists
See an evacuation exit back	PerceiveEvacuationExit	Perceive the nearest evacuation exit in the field of view, if exists
See an exit sign back	PerceiveExitSign	Perceive the nearest available exit sign in the field of view, if exists
See an agent back	PerceiveAgentAheadDirection	Perceive the movement direction of the nearest agent in the field of view, if exists
See a crowd zone back	PerceiveCrowdZone	Perceive the most densely zone, if exists
See a crew member back	PerceiveCrewMember	Perceive the nearest crew member, if exists

Table 3.1: Perceptions responsible for perceive a specific object type. The ones whose name ends in "back" are related to the back vision cone

See a crowd zone perception is inspired in group behaviour. In evacuation scenarios, humans are many times influenced by the density of the crowd. In some cases they are suitable to follow the crowd movement, whereas, in others, they try to avoid exhausted areas and find a new alternative route. Therefore, this perception determines a vector to the most densely populated area. Figure 3.11 describes an example of this perception.

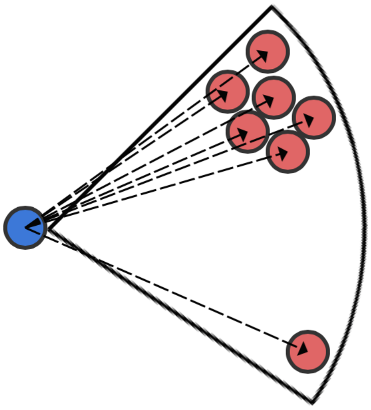


FIGURE 3.11: Crowd density calculation based on agents perceived by the field of view. Red circles represent the passengers perceived by agent (blue circle)

This kind of perception is based on cohesion component of flocking behaviour algorithm. Therefore, every agent inside agent's field of view is considered for the resulting direction vector. A center of mass is then calculated averaging the position vectors of the agents within vision cone.

Crew members take a major influence in the evacuation process. Their gestures and commands are generally received by the passengers, having influence in their evacuation routes. Therefore, *See crew member* perception allows a passenger to perceive whether a crew member is within the field of view.

Perceive Movement Direction

Whenever observed the human behaviour in massive crowds, some individuals tend to follow the movement direction of their neighbourhood. Effectively, it is verified that a higher degree of uncertainty during evacuation process makes individuals follow masses instead of finding an alternative route by their own.

In this sense, an agent is able to perceive the movement direction of the nearest individual within its vision cone. *See an agent ahead* perception indicates whether an agent is within the field of view and holds the corresponded movement direction.

Perceive Potential Deadlocks

During the evacuation process, some individuals change their initial route for different reasons. Some observations suggested that these route changes also have a major influence of the crowd flow direction.

This perception takes a major role when observed re-routing decisions in evacuation scenarios. A good example occurs when an individual is moving towards a given direction along an aisle and perceives another object in the opposite direction. In many cases, no re-routing decisions are taken due to other passengers moving towards the same direction.

Therefore, *Agent ahead direction* is a number perception as defined in *BitBang* architecture. Its integer value represents the dot product between the own agent's movement direction and the nearest agent's movement direction. Table 3.2 shows a description of this perception:

Name	**Class**	**Description**
Agent ahead direction	PerceivePotentialDeadlocks	Indicates the movement direction of the nearest agent in relation to the agent , if exists
Agent back direction	PerceivePotentialDeadlocks	Indicates the movement direction of the nearest agent in relation to the agent , if exists

Table 3.2: Perception responsible for identify the movement's direction of the nearest agent. The ones whose name ends in "back" are related to the back vision cone

This perception is determined as follows:

- Calculate the dot product between the nearest agent's velocity vector and the own velocity vector.
- Define perception value according to the dot product range:
  - **-1**) No other individuals are perceived in the vision cone
  - **0**) Dot product is **negative**.
  - **1**) Dot product is **positive**.

Through this perception, it is possible to verify whether another individual is moving in the same direction of the agent or towards a reverse direction.

Perceive Graph Nodes

As discussed in section 3.2.1.1, the agent's movement over the aircraft enclosure is aided by a graph structure. However, all movements are performed in the continuous space, wherefore several graph nodes are determined as being the next goal nodes. Thus, agents are explicitly able to perceive whether a new temporary goal node is already defined, and take an action according to that. Table 3.3 describes the main components of this perception:

Name	**Class**	**Description**
Has next target node	PerceiveHasNextNode	Indicates whether temporary goal nodes are already defined in the corresponded agent

Table 3.3: Perceive whether the next goals nodes are defined.

Given that different simulation steps and distances between graph nodes are allowed in the proposed model, an agent is able to move himself within a distance greater than the one remaining to the next goal node. It is therefore necessary to ensure two goal nodes at a given moment in order not to observe any time disparities when defined different simulation time steps. Figure 3.12 shows an example of this situation.

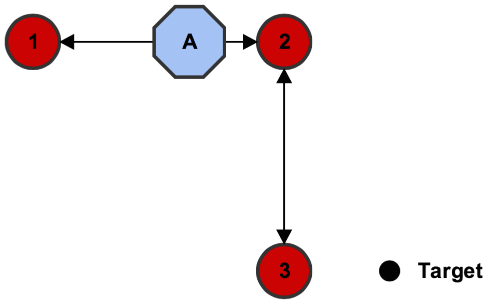


Figure 3.12: Agents' navigation example. Why should be assigned two goal nodes at each simulation step?

In Figure 3.12, agent A has defined node 2 as the temporary goal node because he is seeking the *target* point. In the current simulation step, the agent's velocity allows him to travel a distance greater than the one remaining to reach the goal node (node 2). So, if it was defined one only node, a distance smaller than passenger travel step will be covered. As expected, it could arise some problems in the total evacuation time whenever defined a different step or travel speed. In this specific example, the node 3 is defined as the second node of the agent A.

The perception "Has next node" is evaluated as *true* whenever two goal nodes are already defined in the corresponded agent. Otherwise, the perception value is established as being *false*. The goal nodes are determined by a specific set of actions, as will be discussed in section 3.2.4.3.

This perception is usually placed within a rule with a higher priority than all rules with a consequent action responsible for determining the next goal nodes. However, some specific rules with a consequent action of this type can be placed before a rule with "Has next node" perception. In these cases, the goal nodes can be redefined without the agent even reaching a goal node.

Self-Perceptions

Another important class of perceptions is associated to self-perceptions. Then, the agents are able to perceive their own physical and psychological conditions.

Crowd density

Agents can also perceive the density of passengers within both their vision cones. Therefore, these are *number* perceptions which values indicate the amount of agents within the field of view. Figure 3.4 describes these perceptions.

Name	**Class**	**Description**
Crowd density	BBPerceptionNumber	Indicates the number of agents within agent's field of view
Crowd density back	BBPerceptionNumber	Indicates the number of agents within agent's field of view

Table 3.4: Perceive the number of agents within agent's field of view. The one whose name ends in "back" are related to the back vision cone.

Through these perceptions an agent is able to take decisions according to the crowd density in both vision cones, including the possibility to compare crowd densities between them.

Perceive Memory

As described in section 3.2.4.1, agents are fitted with a memory mechanism. Therefore, a perception is associated to each memory entry with the purpose of perceiving its corresponded value and updating it. Observing Figure 3.10, "PerceiveMemoryLocation" is an abstract perception responsible for manipulating a specific memory entry. In addition to holding a location, its value is a *boolean*, indicating whether the corresponded memory entry is defined or not.

Similarly to *features*, memory entries can be used in rule's conditions. For that purpose, it must be indicated the keyword "Memory" followed by the memory entry name (see example 3.2).

```
IF istrue(Memory Nearest evacuation exit) THEN ...
```

Listing 3.2: Example of memory used in rule list

In the evacuation context, a perception was incorporated to support each memory entry already included in the model (see 3.2.4.1). Table 3.5 describes those perceptions as well as their corresponding classes.

Ready to Exit Self-Perception

Name	**Class**	**Description**
Memory Nearest exit front	PerceiveMemoryNearestExit	Perceives the nearest evacuation exit remembered, whose its location is in front of the agent position
Memory Global nearest exit	PerceiveMemoryGlobalNearestExit	Perceives the nearest exit considering both vision cones
Memory Most familiar exit	PerceiveMemoryLocation	Perceives the most familiar exit recorded in the agent's memory
Memory Exit sign front	PerceiveMemoryExitSign	Perceives the last exit sign in front remember by an agent
Memory Crew member in front	PerceiveMemoryCrewMember	Perceives the last crew member in front remember by an agent

Table 3.5: Perceptions responsible for update and read memory entries included in the model

After moving towards a given evacuation exit, a passenger needs to perceive whether they are ready to leave the aircraft through it. Therefore, "Is ready to exit" perception is responsible for verifying whether the agent is near an evacuation exit. Also, this perception verifies whether the corresponding exit is available or not. Table 3.6 describes this perception.

Name	**Class**	**Description**
Is ready to exit	PerceiveReadyToExit	Indicates whether an agent is near an exit and check exit status

Table 3.6: Perceive whether a passenger is near an evacuation exit

Perceive Passengers In Negotiation Zone

During evacuation process, passengers are subjected to a wide range of scenarios in which other passengers are trying to reach the same physical space. Instinctively, the first one reaching the corresponding space forces the others to wait until it becomes available.

However, humans are mainly distinguished by their rational component and its influence on their behaviour. For this purpose, the proposed model takes into account the rational component associated to these conflict scenarios. For a better understating of this mechanism, Figure 3.13 shows an example of a conflict scenario involving 4 distinct individuals.

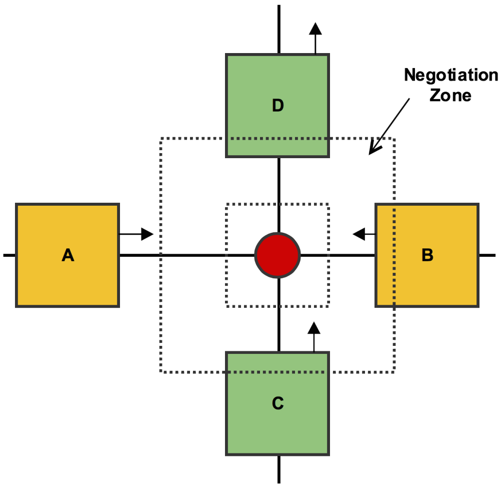


FIGURE 3.13: Example of a conflict scenario where a negotiation process is applied.

Looking at Figure 3.13, it can be seen that both agent B and C are placed within a pre-defined negotiation zone. They are trying to reach the same node, and none of them are within the critical zone. Therefore, it represents a scenario in which two agents are ready to start a negotiation process.

Although many different negotiation mechanisms may be applied, each passenger in the entire simulation has associated a priority value. In this way, this perception will look at other agents placed in the negotiation zone and compare their priority values with the own agent. If a priority agent is seen within the negotiation zone, these perceptions are evaluated as true. Otherwise, it takes the value false.

Perceive whether Entering Into an Aisle

Initial experiments and observations of real world scenarios suggested that some key decisions are taken when a passenger is entering into an aisle. Effectively, it is the instant where passengers decide their initial route to exit the aircraft enclosure. Therefore, an agent is able to perceive whether he or she is entering into an aisle and taking decisions according to that. For this purpose, *Is entering into an aisle* is a boolean perception which value indicates whether the agent is leaving a seat zone.

Density of Passengers Moving To Exit

In addition to encouraging passengers, crew members are also responsible for redirecting them as a way of reducing hypothetical congestion in some exits. For this purpose, crew members are able to perceive the density of passengers (through their vision cones) moving towards their assigned exits. It is a number perception which value indicates the number of passengers in such conditions.

Perceive whether a Passenger is Exiting

One of the most important crew members' duties in evacuation scenarios is encouraging passengers whenever they are approaching an exit. Vocal commands and physical force are the most used techniques to manage exits' flow and avoid long waits.

In the proposed model, a crew member is placed close to an exit and is able to perceive whether a passenger is exiting through it. Unlike the previously presented perceptions, this one resorts to the agent's reach list, once crew members are intended to touch on the perceived passenger. Therefore, *See passenger exiting* is a boolean perception which value indicates whether a crew member perceives a passenger exiting through its assigned exit.

Perceive Flight Attendants Gestures

Many different gestures and vocal commands are performed by the crew members with the purpose of redirecting and stimulating passengers. Once a crew member is assigned to a given exit, he can execute two different gestures: *call passengers to the corresponded exit* or *redirect them to an opposite direction.*

In this way, an individual is able to perceive the gestures being executed by the nearest crew member (through the vision cone) and take decisions according to that. This is a *number* perception whose its values represent the following commands:

-1) No flight attendants perceived with the field of view

0) The nearest flight attendant is **moving passengers away** from its assigned exit

1) The nearest flight attendant is **calling** passengers to its assigned exit

Perceive Opposite Direction

In crowd psychology, some individuals are many times not moving towards a perceived object and can also change their route without any external perception. For example, some passengers in evacuation scenarios change their initial route only because they reached their patience threshold and need to look for a different exit route. Therefore, this perception is responsible for perceiving the opposite movement direction of the agent based on the current one.

Perceive Direction to Forward

This perception is responsible for simply perceiving the current movement direction. In this way, an agent can define the next goal nodes according to the current movement direction, without any influence of an external stimulus.

3.2.4.4 Actions

Many different actions were included in an effort to represent passengers and flight attendants on evacuation scenarios. As will be discussed later (see section 3.2.6), two distinct types of actions are considered as a way of supporting a new inference mechanism than the one already provided by the *BitBang* framework. A general overview of the components associated to these actions is presented in Figure 3.14.

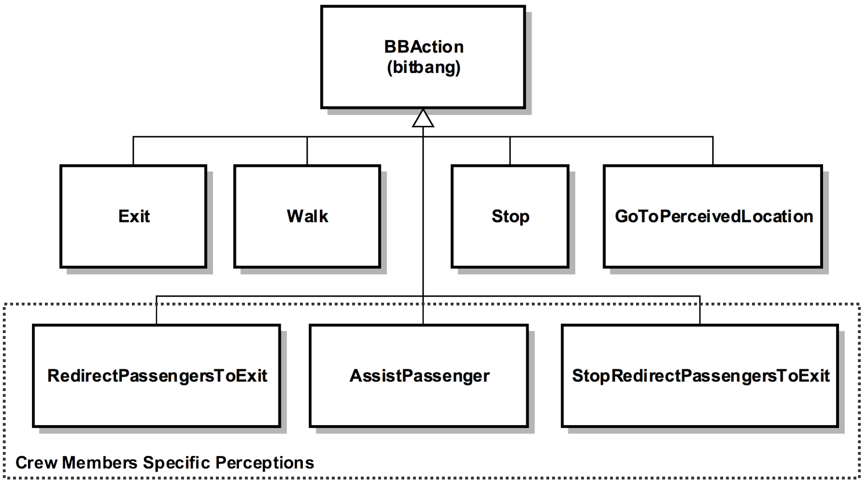


FIGURE 3.14: General overview of the actions included in the model and corresponded architecture

Leave Seat Zone

When initialized a simulation, a passenger starts by moving towards an aisle node. *Go to aisle* action corresponds exactly to this initial movement performed by each agent. For this purpose, a pathfinding algorithm was applied on top of the graph structure in order to find a path to an aisle node.

Although the local behaviour is the main focus of the proposed model, the simplicity associated to the movement along seat zones suggests that a path-finding algorithm to determine the path to the aisle is an acceptable representation of real world scenarios.

In the current prototype, the DFS algorithm was used given that the branching factor of each node is always equals or smaller than 2 (seat neighborhood never exceeds a maximum of 2 seats), increasing the performance associated to this process. This action is rule-bounded being executed as long as a new brain evaluation triggers a different one.

Move Towards a Given Location

As presented in section 3.2.4.2, an agent is able to perceive different objects in the environment and moving toward its location. Therefore, a new class of actions was included in the model as a way of supporting this kind of behaviour. When a perception of this type is executed, the goal nodes are updated according to the target location perceived by the corresponded perception. It is important to note that these perceptions are not directly associated to an external movement of the agent. Table 3.7 shows all the perceptions of this type already included in the model.

Name	**Class**	**Description**
Go to evacuation exit	GoToPerceivedLocation	Determines the goal nodes according to the nearest evacuation exit perceived
Go to exit sign	GoToPerceivedLocation	Determines the goal nodes according to the nearest exit sign perceived
Follow agent ahead	GoToPerceivedLocation	Determines the goal nodes according to the nearest agent (in the field of view) location
Go to crowd zone	GoToPerceivedLocation	Determines the goal nodes towards the most densely zone
Go to crew member	GoToPerceivedLocation	Determines the goal nodes towards the crew member direction
Go to evacuation exit back	GoToPerceivedLocation	Determines the goal nodes according to the nearest evacuation exit perceived
Go to exit sign back	GoToPerceivedLocation	Determines the goal nodes according to the nearest exit sign perceived
Follow agent back	GoToPerceivedLocation	Determines the goal nodes according to the nearest agent (in the field of view) location
Go to crowd zone back	GoToPerceivedLocation	Determines the goal nodes towards the most densely zone
Go to crew member back	GoToPerceivedLocation	Determines the goal nodes towards the crew member

Table 3.7: Actions responsible for calculate the next goal nodes according to a specific object's location. The one whose name ends in "back" are related to the back vision cone.

Once agent's movement is constrained to a space confined to a graph, the vector to the desired location must be approximated to a graph node in order to define the next target node. So, in a naive approach, the next node is chosen considering the *Euclidean distance* between the new position vector and all neighbours of the current node, being chosen the nearest one. Figure 4.12 illustrates an example of this process.

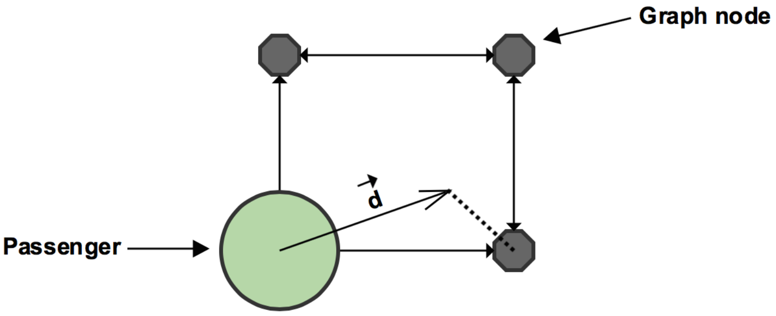


FIGURE 3.15: Illustration of how a direction vector is converted into a movement within the graph

In Figure 4.12, $\vec{d}$ corresponds to a vector pointing to the desired position. The node indicated by a dashed line was the one chosen according to its closest distance to vector $\vec{d}$.

However, an observation of different certification demonstrations suggests that passengers seek for free spaces when moving towards a given location. The most frequent cases occurs when they are close to evacuation exits, particularly the ones connected to large free zones. Therefore, a passenger takes also into account nodes occupation instead of focusing exclusively on the nearest path towards the desired position. Effectively, a shorter distance path may not correspond to the fastest one towards a given location. It is expected that an interesting behaviour can be observed in these free zones given that multiple paths can be chosen towards the same location.

In summary, when determining the next goal nodes, a verification of neighbour nodes is performed, being chosen the nearest one that is free in that moment. When no free nodes are available, it is chosen the nearest one from all the neighbour nodes.

An interesting parameter incorporated in the model indicates a probability of searching for a free node instead of choosing the nearest one. It is associated to each population type and can be seen as a combination of *mental agility* and *goal directed* characteristics of the corresponding passengers. Therefore, the greater the likelihood of finding alternative nodes, the higher is the frequency of passengers changing their movement direction in order to find a better route towards a given location.

Furthermore, another set of preliminary experiments emerged some inconsistent behaviour. In this sense, some issues were identified in the algorithm responsible for calculating the next target nodes towards a given location. Effectively, this algorithm was mainly inspired in the steering behaviour, wherefore some conceptual problems are also associated. Figure 3.16 shows one scenario where this algorithm fails.

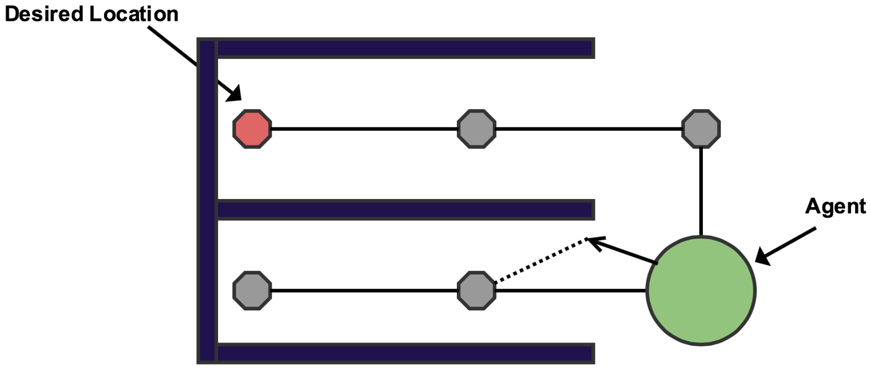


FIGURE 3.16: Example of a scenario where *Euclidean distance* algorithm fails when calculating the next target nodes. In this case, it is chosen a path without connection to the desired location

Observing Figure 3.16, it is clear that target node calculation use *Euclidean distance* can lead to the emergence of some unreal situations when dealing with long range perceptions and some constraints in the nature of the environment. The selected node is effectivelly at a smaller Euclidean distance than all the other ones. However, this path in not directly connected to the target location, wherefore the agent will not be able to reach the target node without going back to the initial node. Indeed, this topic is particularly approached by Millington et. al. [32] when discussing steering behaviour algorithms. To tackle these problems, a path-finding algorithm is pointed out as being the most suitable approach.

In this sense, an alternative method to determine the next goal nodes was studied and incorporated in the proposed model. It was considered the *navigation distance* between two nodes in a graph instead of the Euclidean distance between them. Therefore, the distance between two nodes is calculated according to the length of the shortest path between them. For example, according to Figure 3.16, a different node will be chosen as being the nearest one towards the desired location.

As a way of implementing this mechanism, the well-known *Floyd–Warshall* algorithm was used. This is an algorithm to find the shortest paths in a weighted graph. As main advantage, a single execution of this algorithm calculates the minimum length between two arbitrary nodes belonging to a given graph. However, this algorithm has complexity $O(V^3)$, where V is the number of nodes composing the considered graph. In this way, a single pre-processing execution is performed for a given aircraft specification, wherefore it can be discarded any potential impact in the overall computational performance.

A combination of both algorithms was studied in a effort to find the best representation of the agent's movement. Therefore, it was agreed that a global distance information (using distances calculated with *Floyd–Warshall* algorithm) should be considered whenever perceived evacuation exits. Effectively, these scenarios are mainly associated to long range perceptions with a greater predisposition to these kind of issues, when used an approach based on steering behaviour.

Change movement direction

When observed real evacuations, some individuals change their initial route or assigned exit due to some new perceptions of the surrounding environment. So, it is necessary to consider an hypothetical redefinition of the next goal nodes according to the new target location.

In this sense, two distinct scenarios are considered: when a agent is on a graph node and when he is moving over a connection. In the first case, all target nodes are simply calculated according to the desired direction. In the second one, it is evaluated whether the new position is on an opposite direction of the current goal node. If so, the initial node of the current connection is defined as the next target node and the second goal node is re-calculated according to desired location.

Go to opposite direction

This action determines the next goal nodes according to the perceived opposite direction. In this way, an agent is able to move towards an opposite direction, regardless of any external perception.

Go to direction to forward

This action determines the next goal nodes according to the current movement direction . In this way, an agent is able to move towards a previously defined direction, regardless of any external perception.

Movement

In contrast to the other actions presented in this section, a set of terminal actions are defined in the model. These actions can have an explicit consequence in the agent's movement or changes in the environment.

As observed in real certifications, the evacuation process occurs in an orderly manner, free of aggressive behaviour by the passengers. Also, a high cooperation among passengers is presented in these scenarios. Therefore, the “Walk” action corresponds to a movement towards the next goal node, according to the passenger's velocity.

This action incorporates some steering behaviour components with the purpose of representing a smooth motion as observed in human's movement. Actually, these steering mechanism are only adjusting passengers' speed, without any changes in movement direction. Hence, once defined next target nodes, movement direction is not influenced by "Walk" action. It can exclusively be changed by the rules defined in the agent's brain.

Exit

Whenever close to an evacuation exit, a passenger is able to exit through the corresponding door. However, some personal attributes and environment constraints must be taken into account in these scenarios. Therefore, "Exit" action incorporates all these parameters in order to simulate a real behaviour when passengers are exiting through an exit.

One of these is the time needed by a passenger to pass through a given exit. Effectively, this personal attribute takes a major role in the total evacuation time [46] and is also considered in the proposed model. Furthermore, every exit and their evacuation slide should be ready before passengers start evacuating through them. So, a passenger is only able to use a given exit when it become ready.

Encourage Passenger

The crew members close to an exit are mainly responsible for encouraging passengers who are exiting through a given exit. For this purpose, a crew member is able to take an influence on the *exit delay time* of a passenger who is exiting at a given moment. It is representative of some gestures and vocal commands with an impact on evacuation effectiveness.

3.2.4.5 Brain

As already referred, the brain associated to each agent is defined by a set of logical rules. Each one of them is composed of different perceptions and a consequent action. Despite an inference mechanism was already implemented in the *BitBang* framework, a different one was used in the model with the purpose of obtaining a better representation of human behaviour.

In the *BitBang* framework, the "think" process evaluates each rule and chooses the true one with highest order priority. Therefore, a single evaluation is performed and the selected action is executed. Through this mechanism the same action should be responsible for determining the next graph nodes and executing an explicit movement towards these nodes.

It was considered that a different approach should be used, focusing on a clear distinction between actions responsible for determining the next goals nodes and the ones that provide an explicitly movement towards these nodes. Therefore, each agent is also characterised by an internal state regarding to its next goal nodes.

For example, when a "GoToPerceivedLocation" action is executed, the next goal nodes are calculated according to the perceived location without any modification on agents' position. On the other hand, "Walk" action executes an explicit movement towards the pre-defined goals nodes in a orderly manner. So, there is a clear distinction between actions with an external and internal consequence.

To support this inference mechanism, a forward chaining method was included. In this way, each "think" process starts with the data collected from the environment and internal states, and uses inference rules to extract more data until a goal location is reached. This mechanism starts by evaluating the rules until it finds one where all perceptions are evaluated as true. When such a rule is found, the consequent action is executed being added more knowledge to the agent. This new information will be considered in the next iteration.

Considering this inference mechanism, it is important to distinguish a terminal from a non-terminal actions. The first one does not add any additional information and it's generally associated with an action that brings an external consequence (e.g. movement, environment change). The second one will result in an internal modification of the agent and generally results in activation of different rules in the next iteration.

For a better understanding of this inference mechanism, Figure 3.17 shows an example of a "think" process with 2 iterations.

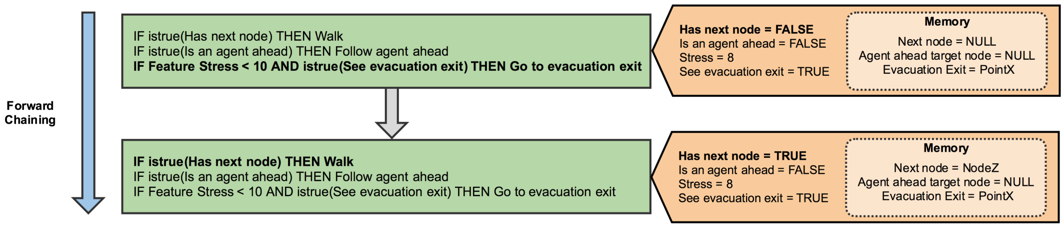


FIGURE 3.17: Example of the new inference mechanism (forward chaining) considered in the model. It are represented two consecutive iterations.

In the example of Figure 3.17, since the agent doesn't have a near node associated and the last rule is evaluated as true, the "Go to evacuation exit" action is executed, being determined the next goal nodes. Given that a non-terminal action was executed, a revaluation of the agent's perceptions is performed and consequently a different rule is activated. Then, the agent starts walking towards the goal nodes defined in the antecedent iteration.

3.2.5 A Different Field of View

As explained in section 3.2.4.2, BitBang framework provides to each agent a vision cone capable of capturing objects within a given range and angle. This means that whenever an agent wants to check the objects behind him, a rotation angle needs to be applied. Alternatively, a separation between body rotation and head rotation (like in humans) could be also considered.

A different approach was adopted based on a modification of the agent's field of view. Therefore, an additional vision cone was associated to a passenger with an opposite direction from the agent's orientation. As result, agents have attributed two vision cones with opposite directions.

However, to model a real human behaviour, back and front vision cones are not updated with the same frequency. Front vision cone is updated whenever an agent is thinking. In other words, before agent's brain evaluation, the front vision cone is updated with the objects currently within it. On the other hand, as back vision cone represents a looking back movement, it is only updated according to a given probability which indicates the frequency in which an agent looks back. As result, an agent can use outdated information on the surrounding environment (given by back vision cone) to make decisions at a given moment. Figure 3.18 shows the new agent's field of view.

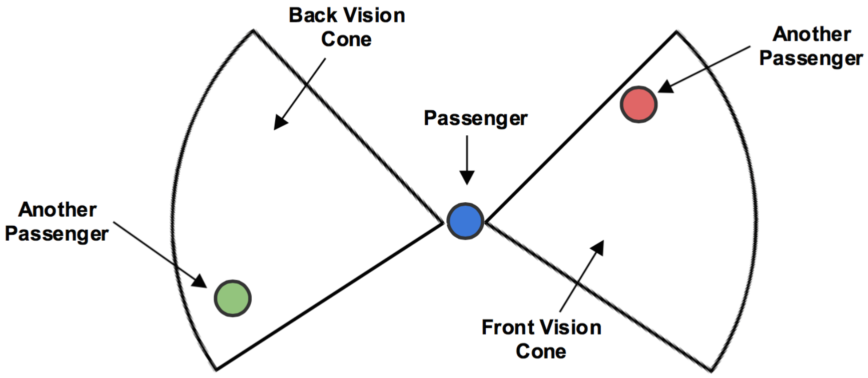


FIGURE 3.18: Representation of agents' back vision with an additional vision cone pointing to an opposite direction

Furthermore, a new algorithm to update both vision cones was conceived in an attempt to improve the performance of this process. As referred in section 3.2.2, a grid map layer was implemented in order to decrease the amount of agents considered in collision verification. Following the same idea, grid map can also be used to restrict which objects should be verified as being within the field of view. This process is shown in Figure 3.19.

According to the situation illustrated in Figure 3.19, only agents partially or totally contained in green cells (represented by red circles) are considered when the field of view

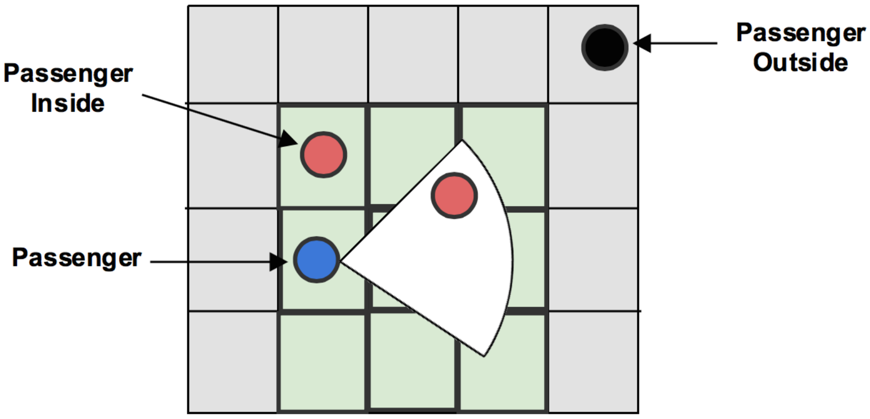


FIGURE 3.19: Field of view update algorithm

is being updated. Despite only described the front vision cone updating mechanism, the same process is applied to the back vision cone.

3.2.6 Human Behaviour Representation

Human behaviour is considered the most important and complex component when modelling a real world scenario [1]. In this section an initial approach to represent human behaviour is discussed.

EvacSafeX seeks a flexible representation of human behaviour, allowing a wide range of agent's behaviour. Therefore, the user can customize different brains, resorting to the perceptions and actions provided by the model.

As presented in section 2.4, some studies identified the most frequent behaviour observed in both certification and real accidents. In this work, human behaviour in certification scenarios will be the major focus. The rule list 3.3 seeks to represent the passenger's behaviour observed in a certification scenario through the components provided by the proposed model.

```
IF istrue(Has next node) THEN Walk
IF istrue(In seat zone) THEN Go to aisle
IF Random Number < Feature Panic THEN Random Walk
IF istrue(See evacuation exit) AND Agent ahead direction < 3 AND Random number
    ↪  1 < 0.6  THEN Go to evacuation exit
IF istrue(See exit sign) AND Agent ahead direction < 3 AND Random number 2 <
    ↪ 0.3 THEN Go to exit sign
IF Agent ahead direction > 2 AND Crowd density front > Crowd density back THEN
    ↪  Go back
```

LISTING 3.3: Example of how brain rules can be used to represent a specific human behaviour in evacuation scenarios

Through the analysis of brain 3.3, it is possible to verify that the rule with highest priority (line 1) is related to a terminal action with an explicitl consequence in the agent's position. Therefore, whenever the goal nodes are already defined, the agent is moved toward these nodes. As long as the goal nodes are being reached, they are re-determined according to the current perceptions on the surrounding environment. In this example, a passenger starts by leaving the seat zone and enter in an aisle in order to define the evacuation route.

Once reached an aisle, different perceptions and psychological conditions will influence the exit choice. Real observations indicate that during certification trials, the passengers are more likely to choose the nearest exit. In this way, the rule 4 indicates that once perceived some evacuation exits, an agent has a probability of 60% of moving towards the nearest one. However, this decision is also influenced by the direction of the nearest agents in the same aisle. Whenever an agent perceives another agent moving in an opposite direction, the rule 4 will be evaluated as false and the rules with a lower priority will be responsible for determining the most suitable action.

The rule 6 seeks to deal with situations in which a passenger perceives another agent moving against him and needs to decide whether a rerouting is need or not. Figure 3.20 represents an example of this scenario in which passenger A is moving according to $\vec{v_1}$ and perceives the crowd B moving against him. In this case, the agent's decision will be influenced by the crowd density (only agents moving along the aisle) of both front and back vision cones. Therefore, when an agent perceives a large amount of passengers moving in an opposite direction, it is expected that he will join the crowd and start moving in the crowd 's direction. Effectively, in certification scenarios the evacuation process happens in an orderly manner and passengers have a cooperative attitude between them.

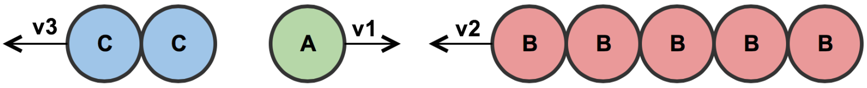


FIGURE 3.20: Example of route modification according to the crowd movement perceived by the agent

Additionally, instead of only considering the crowd's density in both vision cones, movement direction of both groups (considering the direction of the nearest agents in both sides) can be used to improve the representation of this scenarios. Looking at Figure 3.20 , both groups are moving towards the same direction, being irrelevant the density of each group in the decision process.

As already mentioned, crew members are explicitly incorporated in the proposed model. A crew member is able to perceive crowd density and spread passengers over different aircraft zones as a way to avoid bottlenecks at a given evacuation exit. For this purpose, it was considered an algorithm similar to crowd density perception, where each crew member is able to perceive how many passengers are moving towards their assigned exit. Then, passengers can perceive these crew members and follow towards the direction defined in them. Briefly, it represents a real-life scenario where crew members are placed in strategic places over the aircraft, controlling passengers movement through gestures and/or voice commands.

Similarly to passengers, both physical and psychological attributes are associated to crew members. However, they are slightly different, being essentially focused on assertiveness while giving instructions to passengers. Therefore, their rational capabilities can also be influenced by the situation novelty and time pressure.

Chapter 4

Experiments

In this chapter, some validation experiments using EvacSafeX model prototype will be presented and discussed. Firstly, an overview of the case study chosen for the experiments and the corresponding conditions will be presented. Next, a sensitivity analysis of core parameters will be performed as an effort to find their influence in the overall outcome of the simulation. Finally, some experiments will be conducted in an attempt to reproduce real certification demonstrations, being also compared the corresponding results with the ones obtained using *airExodus* simulator.

4.1 Case Study Description

Prior to commencing the evaluation of the prototype, a case study should be considered. This case study will be used for the experiments related to the sensitivity analysis of some core simulator's parameters. Therefore, other aircraft layouts and populations' description will be presented later.

In this case study, an aircraft configuration was chosen according to other studies presented in the literature. However, some specifications are not completely clear (e.g. seat pitch, aisle width), wherefore the considered aircraft architecture corresponds to an approximation of an existing configuration. In this way, the most common specifications are assigned when these are not explicitly presented.

A general overview of the aircraft considered in this case study as well as its discritization onto a graph are presented in Figure 4.1.

This is a narrow-bodied aircraft with a total capacity of 180 passengers (without considering crew member places) and a configuration of 3-3. So, a set of 4 seat blocks, each

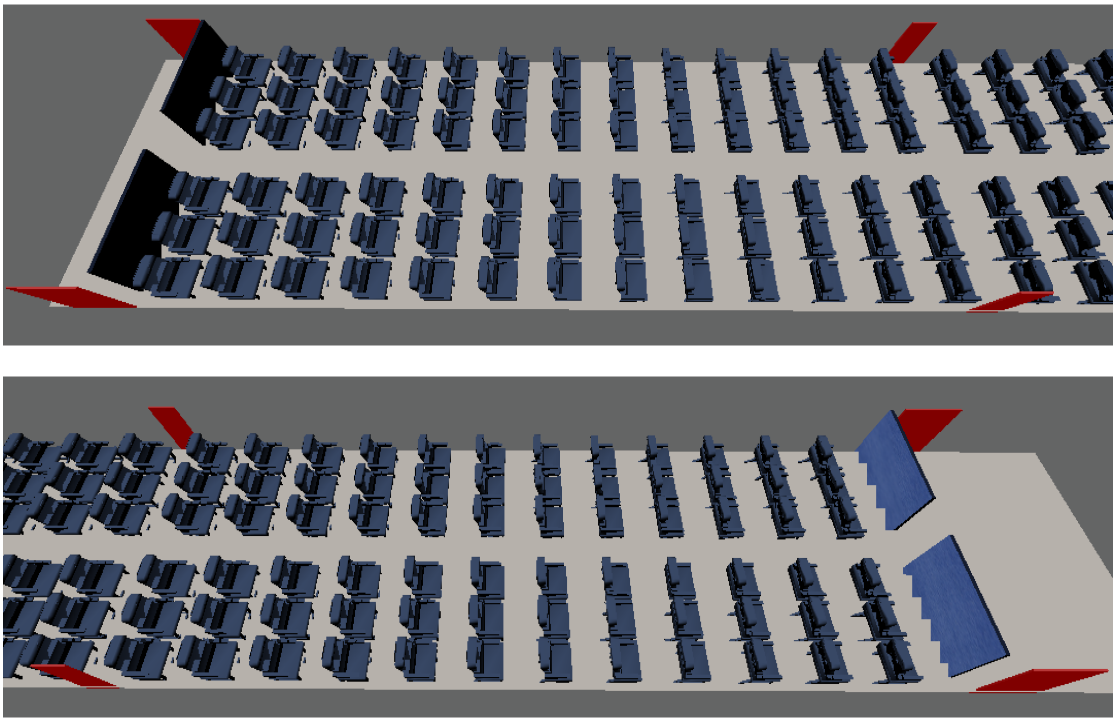


Figure 4.1: General overview of the aircraft considered in parameter sensitivity's experiments.

one with 15 rows and 3 seats per row, is incorporated. One only central aisle is considered with a corresponding width that supports only one person side by side. In total, 6 evacuation exits of two different types are placed in both sides of the aircraft. Two Type 1 exits are located in both lateral sides of tail (back part) and nose (front part) of the aircraft. Once exit width is equal to 86 cm, two distinct nodes are associated to each exit, allowing a simultaneous evacuation of two passengers. These exits are separated from seat zones by walls as shown in Figure 4.1.

Regarding to Type 2 exits, there are two placed in the middle of the aircraft (one on each lateral side), being accessed through the nearest seats row. So, passengers in the corresponded seats' row have a direct access to these evacuation exits without going into the central aisle. These evacuation exits have a width of 40 cm, supporting a single occupant at the same time.

4.2 Generation of Passenger Attributes

Through an analysis of different works available in literature and observations of real certification evacuations, some core passenger's attributes were identified and included in the prototype. Some of them are related to social interactions while others are associated to individual characteristics. These attributes are assigned to each passenger according to a distribution as will be presented next.

An extensive study conducted by E.R. Galea et. al. [3], identified *exit delay time* as one of the most critical aspects in the evacuation outcome. It corresponds to the time spent by a passenger to pass through an evacuation exit. An analysis of data collected from real certification simulations [3] identified that, in general, exit delay time follows an exponential distribution bounded by a minimum and maximum values (see Figure 4.2).

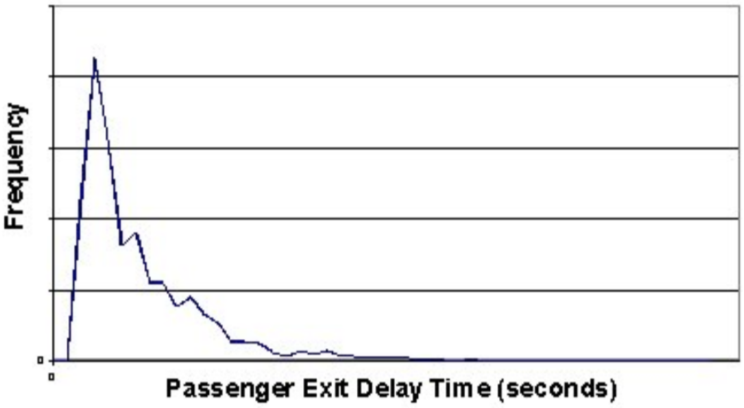


FIGURE 4.2: Exit delay time distribution according to several observations of real certification simulations. Image courtesy of E. R. Galea et. al. [3]

Following these observations, the proposed model prototype generates exit delay time according to an exponential distribution specified by a mean, and bounded by a maximum and minimum values.

Another core personal attribute is associated to the time elapsed since the evacuation call, until the time needed for a passenger to start his evacuation process. For this purpose, these data are randomly generated according to a distribution defined by a mean, a maximum and a minimum values.

4.3 Core Parameters Sensitivity

In this section, some experiments to understand the impact of the change of some parameters is presented and discussed. In every experiment, each configuration is executed 100 times as a way of guaranteeing a statistical representation of the samples. Furthermore, a base configuration was defined considering a single population type with some different personal attributes randomly generated (see section 4.2). Table 4.1 presents the base configuration considered in these experiments.

Personal Attribute	**Values**
Travel speed	Min: 0.8 m/s Max:1.2 m/s
Response time	Mean: 3.93 s Min: 0.02 s Max: 8.0 s
Exit delay time	Mean: 1.5 s Min: 0.2 s Max: 4.0 s
Vision range	17 m
Vision angle	160 °
Vision Reach	0.5 m
Find alternative route probability	0.5

Table 4.1: Individual's attributes defined for the sensitivity's experiments. It includes both physical and psychological attributes.

Apart from passenger's attributes, some configuration parameters of the simulator were defined and are shown in Table 4.2.

Parameter	**Value**
Computational time delta	0.04
Cell size	80
Agent size	40
Conflict zone radius	20
Negotiation zone radius	30

Table 4.2: Simulation parameters considered for the validation experiments.

Regarding to the *computational time delta*, it represents a fixed time step between simulation updates. This way, each time step will have a pre-defined fixed value without any dependence of clock time provided by the operating system. The *cell size* is associated to grid map layer and defines the size of each cell that is part of the grid. Both conflict and negotiation radius are related to the zone of conflict and negotiation, respectively. The first one is responsible for avoiding collisions between agents in interception zones while the second one defines the area in which a passenger can start a negotiation process.

Regarding to the passengers' behaviour, no global rerouting mechanisms are defined, wherefore each passenger evacuates towards a previously assigned exit with an infinite patience. Exit selection was based on real certification observations and studies which identified that in general the nearest exit is chosen, being given priority to frontal and back exits. Exits in the middle are not generally the most used by the passengers. Therefore, exit choice algorithm is responsible for dividing the aircraft enclosure into zones (defined by user) and choosing the passenger's nearest exit within its corresponding zone.

Apart from visual inspection, the results will be compared resorting to other statistical tools. When considering two different configurations, it is used the statistical difference of the null hypothesis of no difference with Mann-Whitney U test and $\alpha = 0.05$. Kruskal-Wallis ANOVAs with $\alpha = 0,05$ will be used whenever comparing more than two samples.

If observed a statistical significant difference between groups, it is performed pairwise Mann-Whitney U tests. All these statistical tests are non-parametric because there are no guarantees about normal distribution of the considered data.

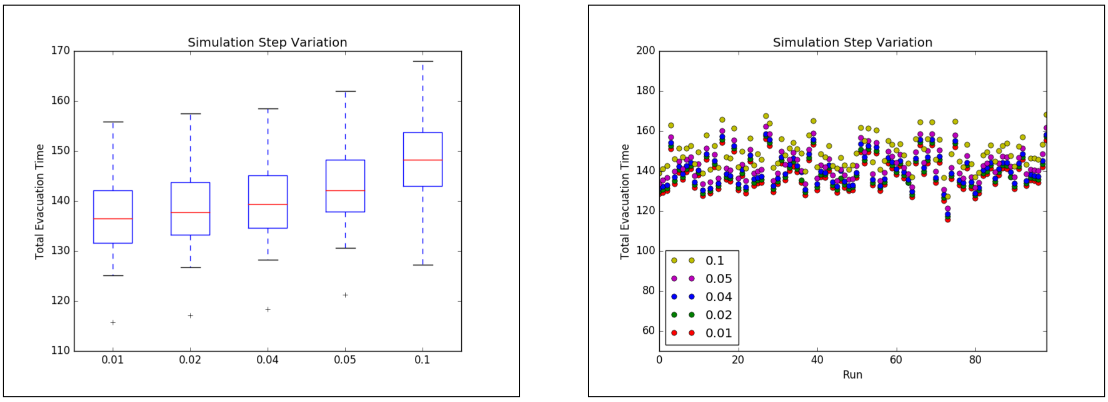
4.3.0.1 Simulation Time Step

Firstly, some experiments were performed considering different simulation steps. Therefore, these experiments have the purpose of understanding what impact the passengers' movement and simulation results would have when used different simulation steps. For this purpose, five distinct simulation steps were considered: 0.01, 0.02, 0.04, 0.05 and 0.1.

The results of these experiments are shown in Figure 4.3. The plot shows that there are some differences between different configurations. Effectively, it was obtained a p-value equals to 3.08×10^{-22}, clearly less than 0.05. A pattern can be observed, suggesting that the greater the simulation time step, the greater the overall evacuation time.

	0.01	**0.02**	**0.04**	**0.05**
0.02	0.002	-	-	-
0.04	1.27×10^{-10}	0.001	-	-
0.05	1.17×10^{-24}	6.09×10^{-18}	5.13×10^{-11}	-
0.1	2.29×10^{-30}	2.01×10^{-27}	2.16×10^{-23}	2.68×10^{-9}

Table 4.3: Pairwise comparisons: influence of simulation step on total evacuation time.



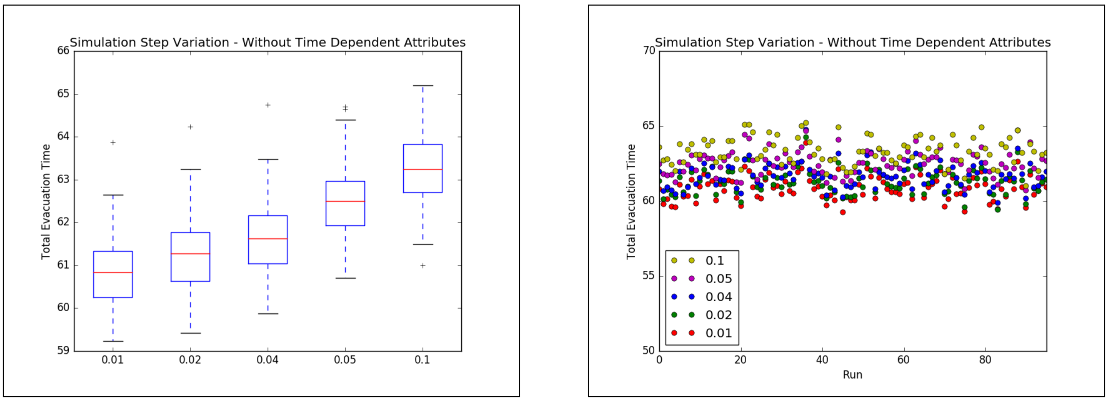
(a) Differences between different simulation steps.

(b) Distribution of total evacuation time when defined different simulations steps. Each color corresponds to a given simulation step.

Figure 4.3: Influence of simulation step in the total evacuation time.

An analysis of these results suggested that probably some attributes associated to both passengers (e.g. response time) or evacuation exits (e.g. exit ready time) might be the source of these deviations between different configurations. In this sense, a set of experiments considering an absence of these attributes was performed. Figure 4.4 presents the results of these experiments.

As can be observed, there is a decrease on the differences between difference simulation steps when considered an absence of some time dependent attributes. Although remaining a statistical difference between configurations, it is shown a difference of 2 seconds between the average values of low and high simulation steps. Effectively, a greater simulation step implies a reduction of time granularity, increasing the error associated to the simulation outcome.



(a) Differences between different simulation steps.

(b) Distribution of total evacuation time when defined different step. Each color corresponds to a given simulation step.

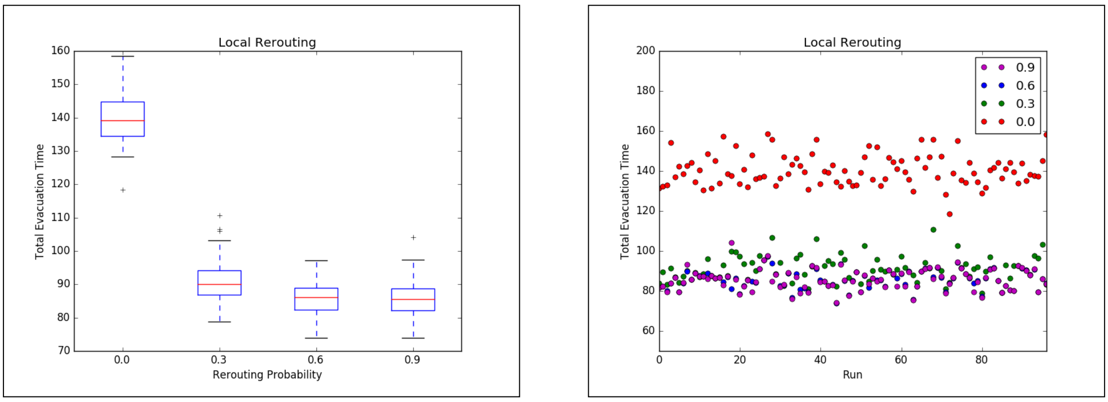
FIGURE 4.4: Influence of simulation step in the total evacuation time when deactivated attributes responsible for simulate the time spent to execute some actions (e.g. response time, exit delay time).

Thus, considering a trade-off between the average error associated to the simulation results and the corresponded computational time spent in each simulation, a simulation step of 0.04 is considered the most suitable one.

4.3.0.2 Local Re-routing Probability

As described in section 3.2.4.3, when executed an action responsible for calculating the next goal nodes, the agents are not simply searching for the shortest one towards a given location. Human attributes such as mental agility and goal-orientation are often associated to crowd behaviour in both pedestrian and traffic scenarios. In the proposed model, a combination of these personal attributes is assumed, giving rise to a probability of taking into account both the distance and occupation of neighbour nodes when calculating the next goals nodes. Therefore, passengers are able to dodge long queues and search for free spaces in order to decrease their personal evacuation time.

To understand the influence of this attribute and perform an analysis of the system behaviour as an whole, three different configurations were compared, considering the same initial conditions and assuring the same random seeds in similar runs of each configuration. Figure 4.5 presents a plot of the results obtained for three configurations with distinct re-routing probabilities: 0.0, 0.3, 0.6 and 0.9.



(a) General overview on the differences of total evacuation time distributions when defined distinct local re-routing probabilities.

(b) Distribution of the total evacuation when defined different re-routing probabilities. Each color represents a different probability valu.e

FIGURE 4.5: Impact of the re-routing likelihood variation on the total evacuation time.

In a general overview, it is clear that an absence of local re-routing leads to a large increase of the total evacuation time. Indeed, it was obtained a p-value equals to 1.54×10^{-52}, showing a significant difference between the considered configuration. Figure 4.4 make it clear that an absence of local-rerouting mechanism provokes a significant increase on the total evacuation time.

For a better understanding of this phenomena, a visual inspection of an aircraft zone with multiple paths towards the same location was performed. Figure 4.6 shows passengers' behaviour in one of these zones. It is possible to verify that passengers don't change their route towards the evacuation exit even though a free space is available. Clearly, this kind of behaviour does not represent the one observed in real evacuation scenarios.

	0.0	**0.3**	**0.6**
0.3	1.233×10^{-33}	-	-
0.6	1.234×10^{-33}	2.88×10^{-9}	-
0.9	1.234×10^{-33}	1.60×10^{-9}	0.39

TABLE 4.4: Pairwise comparisons: influence of local-rerouting mechanism on total evacuation time.

On the other hand, a considerable decrease of total evacuation time is observed when considered a local rerouting. Effectively, through an observation of passengers' behaviour in these experiments, it is clear that the greater the likelihood of find a free space, the

FIGURE 4.6: Emergent phenomena observed when considered an absence of local rerouting probability.

greater the movement frequency in that zone. However, some high total evacuation time values were observed when defined a high probability value. According to a visual observation of these experiments, it happens due to a disorderly crowd behaviour provoked by a permanent changing of individuals' route.

For a better understanding of rerouting influence, Figure 4.7 shows a scenario in which several passengers are moving side by side taking a maximum advantage of the available space and exit capacity.

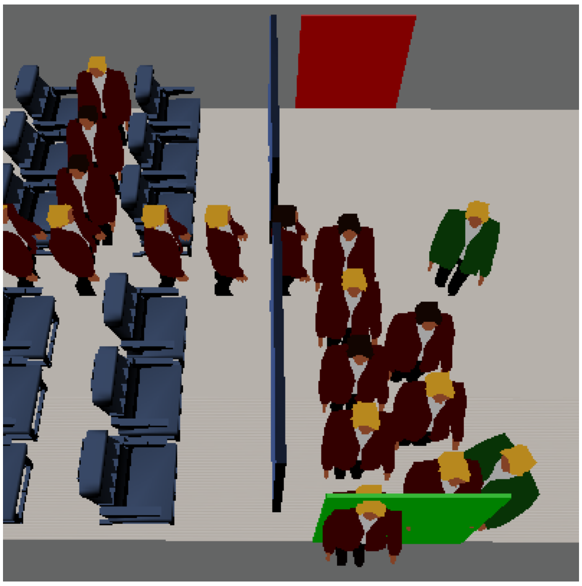


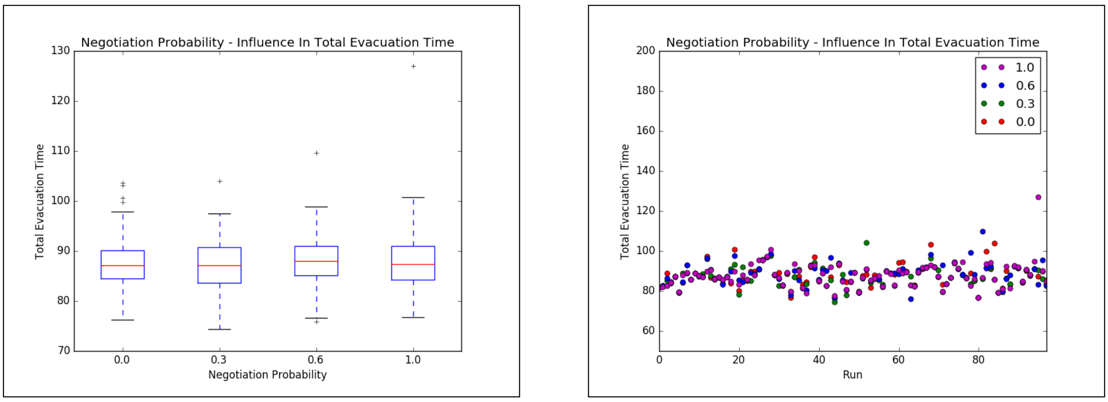
FIGURE 4.7: Example of how local re-routing probability can influence egress.

4.3.0.3 Negotiation Probability

In a rational manner, humans take cooperative actions between them in many ways. When observed aircraft evacuation scenarios, probably the most frequent happens while passengers are entering into central aisles in order to move towards a given exit. Effectively, although all passengers search for a fastest evacuation from the enclosure, some of them stop their movement as a way of allowing others to enter into the aisles. This kind of cooperative behaviour takes a major role in certification scenarios and can be observed with a high frequency through video recordings.

As discussed in section 3.2.4.2, the passengers in the proposed model have the capacity of perceiving whether other passengers are trying to compete for the same space, and taking decisions according to that. This kind of behaviour is explicitly defined in the brain rules and has associated a corresponding probability. Thereby, it is possible to represent different altruism levels through an adjustment of the likelihood associated to a rule responsible for this kind of behaviour.

An impact study of the passengers' altruism level on the evacuation performance will be presented and discussed in this section. The results obtained in these experiments are shown in Figure 4.8, where a comparison of total evacuation time for different negotiation probabilities is conducted. It was obtained a p-value equals to 0.826, indicating no significant differences between distinct negotiation probabilities on the total evacuation time. Figure 4.8 clarifies this phenomena.



(a) Distribution of total evacuation time when defined different local re-routing probabilities.

(b) Total evacuation time obtained in each simulation run, when changed local re-routing probability.

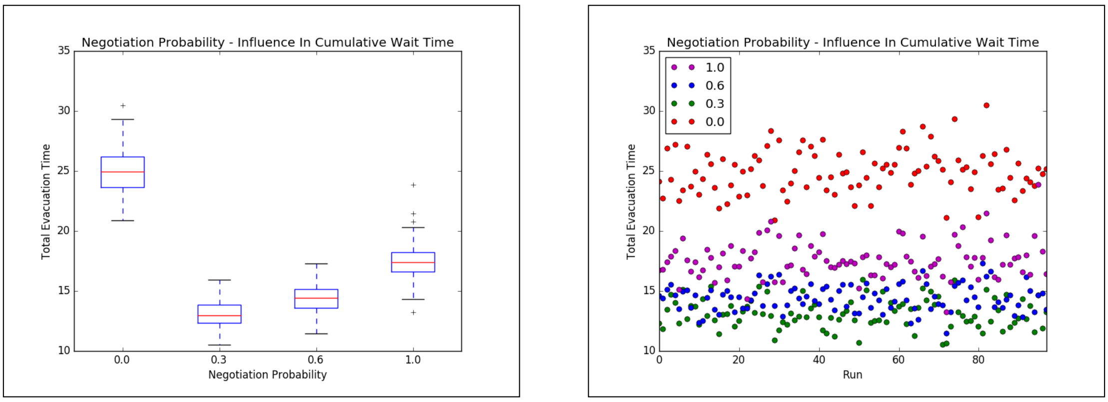
FIGURE 4.8: Results obtained when defined different negotiation probability values.

However, some interesting results were obtained for the cumulative wait time measures. Through an observation of Figure 4.9, it is verified that without cooperative behaviour between passengers, an increase of average cumulative wait time occurs. Furthermore, through a statistical analysis, it was obtained a p-value of 9.755×10^{72}, suggesting a significant influence of this attribute on the cumulative wait time. Effectively, this behaviour matches the one observed in real evacuation scenarios where some passengers are waiting several seconds to enter the central aisle. It often occurs due to a low altruism behaviour and a major instinctive component.

Furthermore, a high cooperation between passengers has associated an increase of the cumulative evacuation time mean. Through a visual inspection, it is possible to verify that many passengers are sometimes waiting long periods of time for other passengers with a higher priority. In some cases, these passengers have less motor capacities, leading to a consequent decrease of the queue average speed.

	0.0	**0.3**	**0.6**
0.3	5.8×10^{-34}	-	-
0.6	5.8×10^{-34}	5.47×10^{-12}	-
1.0	1.69×10^{-33}	7.92×10^{-33}	1.66×10^{-29}

Table 4.5: Pairwise comparisons: influence of negotiation probability on cumulative wait time.



(a) Distribution of cumulative wait time when defined different local re-routing probabilities.

(b) Cumulative wait time obtained in each simulation run, when changed local re-routing probability

Figure 4.9: Results obtained for cumulative wait time when defined different negotiation probability values.

4.4 Global Rerouting Analysis

As already referred, it is expected that an user will be able to represent different individual behaviour when using the *EvacSafeX* prototype. Effectively, an adjustment of passenger's attributes and brain rules have a major importance for that purpose. Probably the most interesting one involves the emergent phenomena when combined multiple perceptions and actions provided by the model. For this purpose, different experiments were conducted as a way of studying the evacuation outcome when assigned distinct rational capabilities to the passengers.

In contrast to the experiments presented in section 4.3, the initial assigned exits were defined according to the nearest global exit of each passenger. Effectively, it follows the initial conditions observed in real evacuation scenarios in which a large majority of passengers find their nearest exits when starting their evacuation process. Concerning the population attributes, similar distributions to those used in section 4.3 were considered. The most familiar exit was randomly defined among the Type I exits available on the aircraft, as a way of representing the door used for loading.

As an effort to represent human behaviour in evacuation scenarios, an iterative process was adopted where different rules were being incorporated in the agents' brain, followed by some validation experiments. For this process, a visual observation of both local and global phenomena was performed with the purpose of understanding which behaviours were inconsistent with the ones observed in real life scenarios.

A first attempt to represent passengers behaviour in these scenarios resulted in the brain 4.1.

```
1  IF istrue(Is ready to exit) THEN Exit
2  IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 50
      ↪ THEN Stop
3  IF istrue(Has next node) THEN Walk
4  IF istrue(In seat zone) THEN Go to aisle
5  IF istrue(See evacuation exit back) AND Agent direction back < 1 AND Feature
      ↪ Patience < 50 AND Crowd density front > Crowd density back THEN Go to
      ↪ evacuation exit back
6  IF istrue(Memory Nearest evacuation exit front) THEN Go to nearest exit front
      ↪ in memory
7  IF istrue(See evacuation exit) THEN Go to evacuation exit
8  IF istrue(Memory Most familiar exit) THEN Go to most familiar exit in memory
```

Listing 4.1: An initial attempt to include re-routing decisions in the passengers' behaviour.

The first rule presented in the brain 4.1 indicates that a passenger starts exiting through an available evacuation exit according to a given exit delay time whenever facing it. Regarding to negotiation, the rule 2 specifies that in 50 per cent of the cases an agent stops to allow a priority agent to enter into the aisle.

The rule 5 is probably the most interesting one, since it intends to represent passengers' behaviour while perceiving long waits. As focused in section 3.2.4.1, the patience level takes a major role when passengers are facing a congestion zone. Also, passengers' movement direction is influenced by the queue flow direction. Indeed, it is not expected that an individual starts moving on an opposite direction after has joined a given queue (e.g. entering into a single queue aisle). Otherwise, it could give rise to conflicts between individuals, not observed in certification scenarios.

Finally, a passenger seeks for its nearest exit in memory. However, it only takes into account the perceived evacuation exits in its front, being discarded all the others in the aircraft.

Once some experiments have been executed, some unresolved deadlocks were observed and a consequent set of unfinished simulations. In some cases, rerouting rules were not reached due to the collisions occurred while the agent was moving over a connection. Effectively, this result can be explained by a wrong order in the brain rules. Whenever an agent is not placed in a node, "Has next node" perception is evaluated as true, disabling rerouting rules to be executed.

To tackle this problem, the proposed rule list was reviewed in an attempt to find a right order, representative of the desired behaviour. In this sense, every rule which execution might influence the current target node must have a higher priority than the ones with an external influence in the agent's movement. These rules can be executed even when both goal nodes are already defined. Following this approach, a redefinition of the previously brain (see brain 4.1) resulted in the brain 4.2.

```
1  IF istrue(Is ready to exit) THEN Exit
2  IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 50
       ↪ THEN Stop
3  IF not(In seat zone) AND istrue(See evacuation exit back) AND Agent direction
       ↪ back < 1 AND Feature Patience < 50 AND Crowd density front > Crowd
       ↪ density back THEN Go to evacuation exit back
4  IF istrue(Has next node) THEN Walk
5  IF istrue(In seat zone) THEN Go to aisle
6  IF istrue(Memory Nearest evacuation exit front) THEN Go to nearest exit front
       ↪ in memory
7  IF istrue(See evacuation exit) THEN Go to evacuation exit
8  IF istrue(Memory Most familiar exit) THEN Go to most familiar exit in memory
```

Listing 4.2: New brain version with a right priority definition to represent rerouting decisions.

As can be verified, the rule 3 is now placed before the one responsible for the "Walk" action. However, the user should pay a special attention whenever using this mechanism. It should be ensured that the rules with a higher priority are only executed on restricted conditions. If not, it is reached an infinite cycle where no terminal actions are executed. For example, the rule 3 in the brain 4.2 is only executed when feature "Patience" is less than a given threshold.

For this purpose, some changes were performed while determining passenger's patience level. Effectively, some observations of human behaviour in real world scenarios suggest that whenever an individual takes an action which changes movement direction, its patience is partially restored until he receives new perceptions from the environment.

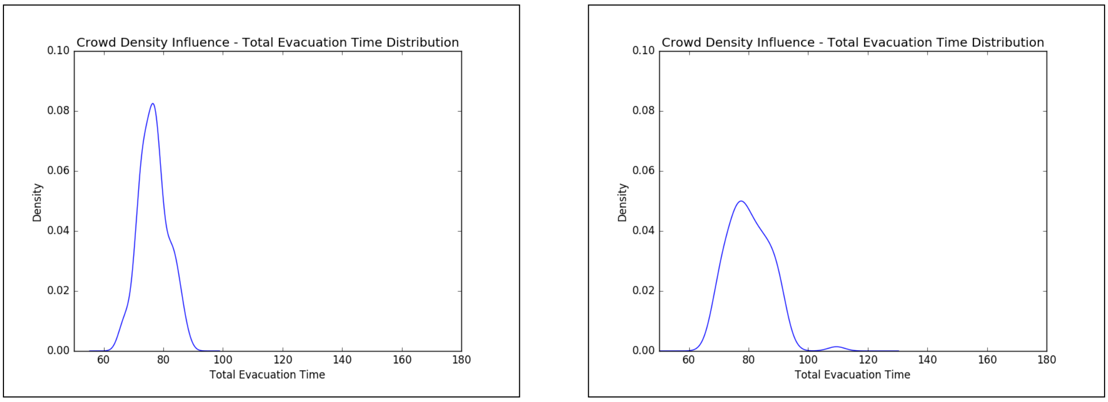
For example, if an individual is waiting in a queue for a long time and decides to leave it, moving towards a different direction, its patience is restored during a certain amount of time. Otherwise, a continuously changing of passengers' movement direction could be verified when analyzed video tapes from real world scenarios.

In this way, the rule 3 is only executed in specific situations, being avoided some constant changes in the passengers' movement direction. Therefore, patience level is recovered after a passenger changes its global target evacuation exit as a way of achieving an accurate representation of these real scenarios.

4.4.1 Crowd Density Influence

Another interesting aspect in the brain 4.2 is related to the fifth perception of the rule 3. As can be verified, passengers are taking into account crowd density in both directions before considered an hypothetical re-routing. Indeed, human decisions in these situations are often influenced by gradient modifications, wherefore individuals seek for the less congested zones. Therefore, a route modification is only conducted when a passenger perceives that the hypothetical new zone is less congested than the current one.

However, it is important to understand the impact of crowd density in the total evacuation time. For this purpose, two different experiments were executed, considering two different brains: one with crowd density comparison before performing a rerouting and another one without taking it into account. Figure 4.10 shows the density plots of both configurations.



(a) Influence of crowd density when a passenger decides to change its current movement direction.

(b) Total evacuation time obtained in each simulation run, when taken crowd density into account.

Figure 4.10: Results obtained for total evacuation time when compared re-routing decisions with and without crowd density aspect.

As can be seen in Figure 4.10, there is a difference between mean evacuation time values of both configurations. It was obtained an average evacuation time of 76.70 seconds when considered crowd density and 80.18 seconds when discarded this aspect. Another interesting point is related to the standard deviation in both experiments. It was observed a greater value when a rerouting is performed independently of the crowd density. This phenomena can be justified by the greater random component associated to the passengers' behaviour. Effectively, passengers are more likely to choose a decision which increases their evacuation effectiveness when considered crowd density in rerouting decisions. On the other hand, an absence of this component gives rise to some wrong decisions with a consequent negative impact in the evacuation process.

When resorted to a visual observation without taking crowd density into account, it can be confirmed that some passengers leave their current queue after reached their patience threshold, joining another one notably congested. In a global manner, there is also some unreal behaviour without considering crowd density, in the sense that many passengers are changing their movement direction continuously for merely reaching their acceptable patience level.

However, humans are often not perfect when acting and their perceptions are many times subject to many influences. Therefore, a combination of both cases can be considered the most correct way to model this specific scenario. For this purpose, one can combine two rules (one considering crowd density and another without taking it into account) with a stochastic perception associated, as represented in the brain 4.3.

```
1  IF istrue(Is ready to exit) THEN Exit
2  IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 50
       ↪ THEN Stop
3  IF not(In seat zone) AND istrue(See evacuation exit back) AND Agent direction
       ↪ back < 1 AND Feature Patience < 50 AND Random number 2 < 30 THEN Go to
       ↪ evacuation exit back
4  IF not(In seat zone) AND istrue(See evacuation exit back) AND Agent direction
       ↪ back < 1 AND Feature Patience < 50 THEN Go to evacuation exit back
5  IF istrue(Has next node) THEN Walk
6  IF istrue(In seat zone) THEN Go to aisle
7  IF istrue(Memory Nearest evacuation exit front) THEN Go to nearest exit front
       ↪ in memory
8  IF istrue(See evacuation exit) THEN Go to evacuation exit
9  IF istrue(Memory Most familiar exit) THEN Go to most familiar exit in memory
```

LISTING 4.3: Example of a brain which represents the bounded rationality associated to the human behaviour.

Observing the brain 4.3, it is shown that both rules 3 and 4 are almost identical. They should not be analyzed in independent ways. They indicate that a passenger doesn't take crowd density into account when deciding whether another exit should be chosen, in 30%

of cases. Effectively, this mechanism can be seen as the *bounded rationality* associated to the human individuals. It was introduced by James March et. al. [47], identifying human rationality as being bounded due to the fact that neither every perceptions nor every actions are considered in the rational decision process.

4.5 Initial Egress Route

Many observations of real evacuation scenarios and certification trials show that the direction taken by the passengers when entering into an aisle has a major influence in the evacuation process. Indeed, some studies identified the most common behaviour observed in these situations [48–50], through a set of questionnaires and video recordings. In this sense, some passengers took the same route of the ones in their front, whereas others followed the crew members instructions. Furthermore, some of them tried to find the nearest exit or moved towards the one used in loading.

Some new brains were defined with the purpose of representing these observations. The next sections are precisely dedicated to explaining how these behaviours were represented in the EvacSafex model, figuring out which perceptions and actions were used for that purpose. Also, the results obtained in these experiments will be presented as well as the corresponding impact on the evacuation effectiveness.

4.5.1 Choose the Nearest Exit

Both in certification scenarios and real accidents, some passengers are mainly influenced by the exits that are perceived during the evacuation process. As already refered in 2.4, although this behaviour is most commonly observed in real accidents, it cannot be discarded from certification cases. Effectively, these passengers start perceiving the surrounding exits from the moment they are moving from their seat zone to an aisle. Furthermore, some studies demonstrated that, in general, the passengers have a prior knowledge of the exits' location and how far they are from them.

In this way, each passenger in these simulation experiments knows the location of its global nearest exit. It must be remembered that this memory location can be updated during the simulation, according to the new exits that are being perceived. Therefore, it is desirable that a passenger starts moving towards its global evacuation exit whenever leaving its seat zone. An attempt to represent this behaviour resulted in the brain 4.4.

```
IF istrue(Is ready to exit) THEN Exit
IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 50
    ↪ THEN Stop
```

```
3  IF not(In seat zone) AND istrue(See evacuation exit back) AND Agent direction
     ↪ back < 1 AND Feature Patience < 50 THEN Go to evacuation exit back
4  IF istrue(Has next node) THEN Walk
5  IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(
     ↪ Memory Global nearest exit) AND Random number 2 < 30 THEN Go to global
     ↪ nearest exit in memory
6  IF istrue(In seat zone) THEN Go to aisle
7  IF istrue(Memory Nearest evacuation exit front) THEN Go to nearest exit front
     ↪ in memory
8  IF istrue(See evacuation exit) THEN Go to evacuation exit
9  IF istrue(Memory Most familiar exit) THEN Go to most familiar exit in memory
```

LISTING 4.4: The brain obtained in an attempt to represent a set of individuals with an initial movement towards their nearest exits.

As can be observed in the brain 4.4, a new rule was introduced as a way of representing the initial movement towards the passengers' global nearest exit. Therefore, the rule 5 indicates that a passenger moves towards its nearest exit whenever entering into an aisle. Also, it can be noted that rule 5 has associated a random perception, wherefore this behaviour will occur according to a given probability.

In order to understand how this new rule can influence the evacuation process, some experiments were conducted with different probabilities of executing an initial movement towards the nearest exit. Figure 4.11 shows a comparison between different configurations.

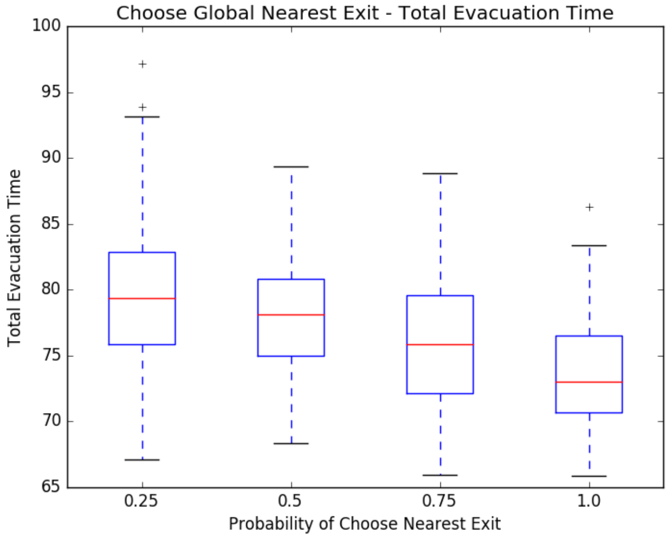


FIGURE 4.11: Results obtained for different probabilities of execute an initial movement towards the nearest exit. It is observed that a major influence is associated to this initial action.

Observing Figure 4.11, it is possible to verify that the initial decision takes a major rule in the total evacuation time. Effectively, a greater probability of moving towards the nearest exit when entering into an aisle reduces the total evacuation time. Furthermore, it was obtained the lowest standard deviation when passengers take an initial route towards their nearest exit, suggesting a better organizational capacity without persistent bi-directional flows.

Through a visual inspection of these experiments, it is observerved an increasing number of conflicts between passengers when defined a low probability. In a general manner, these conflicts emerge due to multiple flows with opposite directions, being necessary a consequent conflict resolution. Indeed, several passengers start moving towards an exit perceived at a given moment (generally not the nearest one), without taking flow direction into account.

4.5.2 Herding Behaviour

Human behaviour in evacuation scenarios is also characterized by a strong social component. Effectively, an individual can be influenced by the other ones during its egress. Some studies identified that many individuals tend to follow the masses instead of taking selfish decisions [48].

In this sense, it was studied a mechanism able to represent this kind of behaviour in the proposed model. The herding behaviour is primarily taken whenever a passenger is leaving his seat zone and entering into an aisle. In these scenarios, the nearest neighbour's movement direction has a major influence on the route taken by the passenger. An effort to represent this herding behaviour component resulted in the brain 4.5.

```
IF istrue(Is ready to exit) THEN Exit
IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 50
    ↪ THEN Stop
IF not(In seat zone) AND istrue(See evacuation exit back) AND Agent direction
    ↪ back < 1 AND Feature Patience < 50 THEN Go to evacuation exit back
IF istrue(Has next node) THEN Walk
IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(
    ↪ Memory Agent ahead direction) AND Random number 2 < 30 THEN Go to agent
    ↪  ahead direction in memory
IF istrue(In seat zone) THEN Go to aisle
IF istrue(Memory Nearest evacuation exit front) THEN Go to nearest exit front
    ↪ in memory
IF istrue(See evacuation exit) THEN Go to evacuation exit
IF istrue(Memory Most familiar exit) THEN Go to most familiar exit in memory
```

Listing 4.5: The brain considered to represent herding behavior when an individual is entering into an aisle.

Similarly to the experiments in which passengers seek the nearest exit, it was verified that every decision taken when entering into an aisle has a major influence on the total evacuation time (see Figure 4.12). Effectively, a higher probability of following neighbours gives rise to a better organization between passengers, decreasing the number of conflicts between them. However, a visual inspection of these experiments makes it possible to verify that the passengers seated close to an aisle are crucial in the remaining evacuation process. The route of every passenger placed nearer a window are mostly influenced by the ones already traveling over an aisle.

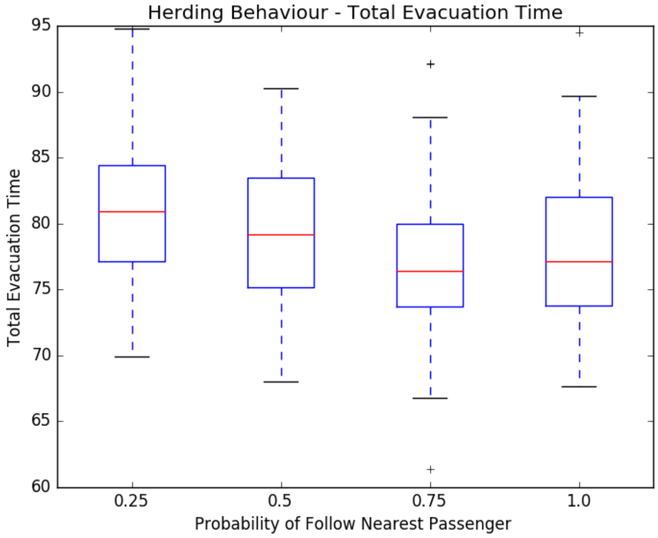


Figure 4.12: Results obtained for different probabilities of execute an initial route according to the neighbors' movement direction. It is observed that a major influence is associated to this initial action.

Through an analysis of these results, it was verified that some simulations presented a total evacuation time higher than the average. Some passengers seated along the aisle were preponderant in the simulation outcome. Effectively, their initial decisions had an influence on the other passengers, determining their movement direction when leaving seat zone.

In some cases, many passengers performed an initial movement towards similar directions, provoking a clear congestion in some evacuation exits. Consequently, other exits were not used for long periods of time, wherefore some passengers only decided to move towards them when reached their patience levels and started moving according to an alternative egress route.

4.5.3 Follow Crew Members Instructions

As discussed in section 2.4, the crew members have a major influence in the evacuation process. Effectively, they are responsible for conducting the passengers, being preponderant in their route choices. Some perceptions and actions were included in the model with the purpose of representing crew members. Therefore, a set of experiments was conducted as a way of understanding their impact in an overall effectiveness of the passengers' egress.

In a general manner, many passengers are mostly influenced whenever they are moving from their seats to a given aisle. They tend to accept crew members' gestures and take an initial route towards the suggested directions. For this purpose, the brain 4.6 represents a population whose initial movement is performed towards the nearest crew member perceived in its front.

```
IF istrue(Is ready to exit) THEN Exit
IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 50
    ↪ THEN Stop
IF not(In seat zone) AND istrue(See evacuation exit back) AND Agent direction
    ↪ back < 1 AND Feature Patience < 50 THEN Go to evacuation exit back
IF istrue(Has next node) THEN Walk
IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(
    ↪ Memory Crew member) AND Random number 2 < 30 THEN Go to crew member in
    ↪ memory
IF istrue(In seat zone) THEN Go to aisle
IF istrue(Memory Nearest evacuation exit front) THEN Go to nearest exit front
    ↪ in memory
IF istrue(See evacuation exit) THEN Go to evacuation exit
IF istrue(Memory Most familiar exit) THEN Go to most familiar exit in memory
```

Listing 4.6: The brain considered to investigate whether initial decisions considering crew member's gestures have a major influence in the egress.

A crew member considered in these experiments is continuously performing gestures without any criteria, trying to call passengers to its assigned exit. Figure 4.13 presents how crew members are distributed over the aircraft enclosure.

Similarly to the experiments conducted in the previous sections, it was analyzed whether a significant impact is observed in the evacuation outcome, when passengers are more likely to follow crew members instructions. Figure 4.14 shows the results obtained in these experiments.

Clearly, the crew members have a positive impact in the total evacuation process. Indeed, it is verified that the higher the probability of following crew members' instructions, the shorter the average total evacuation time. However, an interesting phenomena is verified in the distribution of simulation results when considered a probability of 100%. In the initial seconds after the evacuation call, it is observed that many passengers are trying to reach the same exit, influenced by a perceived crew member. Consequently, a small amount of passengers is choosing the exits at the middle, resulting in an increase of the evacuation time. Figure 4.15 represents these situations.

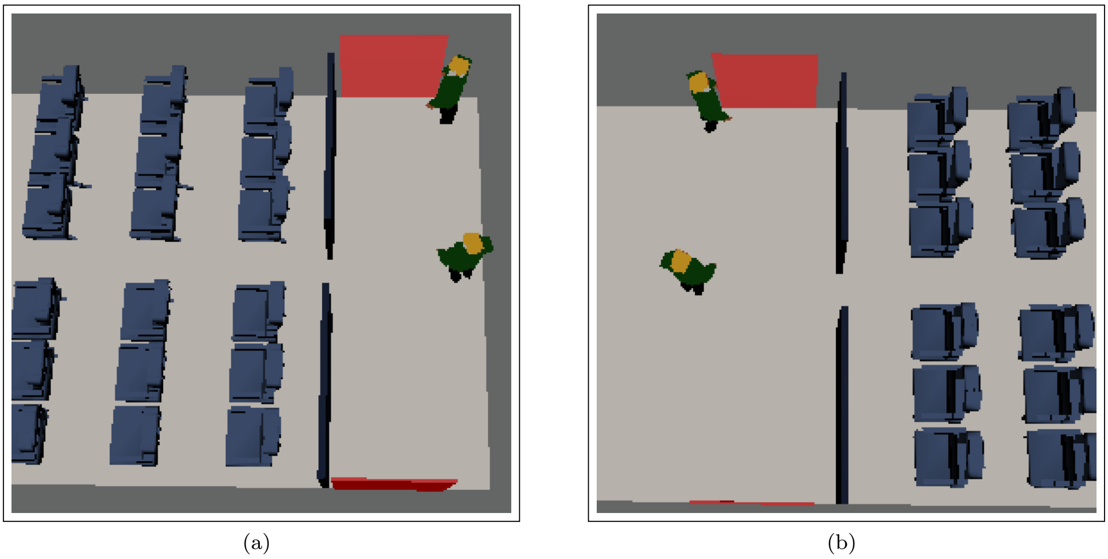

(a) (b)

Figure 4.13: Distribution of the crew members on the aircraft. They were placed in strategic position as a way of encourage or call passengers.

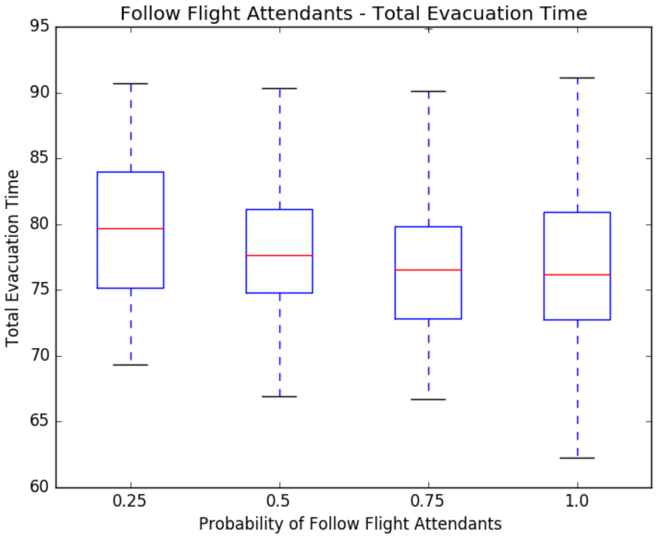


Figure 4.14: Results obtained for different probabilities of execute an initial route according to the perceived flight attendants' gestures. It is observed that a major influence is associated to this initial action.

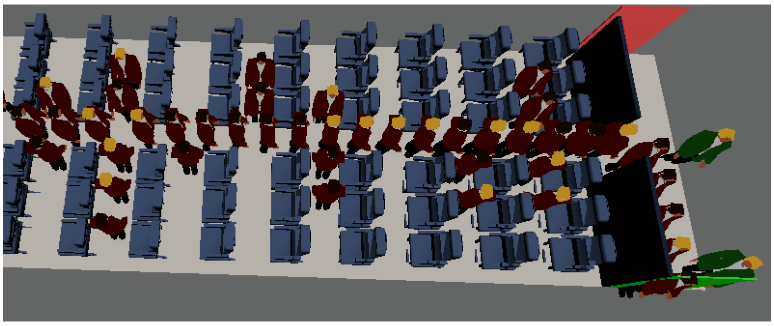


Figure 4.15: Visual inspection of the emergent phenomena observed when many passengers take an initial route according to crew members' gestures.

4.6 Multiple Flow Directions

After a careful investigation of the experiments conducted in the previous sections, a strange behaviour was observed in some of them. As already discussed, opposite flow directions can be observed when a passenger choose its evacuation route without taking flow direction into account.

Observing the brain 4.6, these conflict scenarios are solved through the rule 3. In this way, a redirection decision is directly dependent on the patience level, wherefore a passenger trying to move in an opposite direction until its patience is reached. Clearly, this is not in accordance to crowd behaviour observed in certification scenarios. Humans are generally influenced by the crowd flow direction, adjusting immediately their routes to that direction.

Particularly in aircraft evacuation, it is observed that many passengers moving along an aisle change immediately their initial route, whenever perceived a queue moving in an opposite direction (considering the same aisle). Otherwise, it will be verified an inconsistent evacuation process, without cooperation, and a continued conflicts of wills. Therefore, it doesn't make sense to attach patience level to these conflict cases, suggesting a different approach to deal with them. The brain 4.7 represents an improved version of the brain considered in the previous experiments, presenting a new rule responsible for solving these conflict scenarios.

```
1  IF istrue(Is ready to exit) THEN Exit
2  IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 80
       ↪ THEN Stop
3  IF not(In seat zone) AND Agent movement direction front = 0 AND Agent movement
       ↪  direction back < 1 AND istrue(See evacuation exit back) THEN Go to
       ↪ evacuation exit back
4  IF not(In seat zone) AND istrue(See evacuation exit back) AND Agent movement
       ↪ direction back < 1 AND Feature Patience < 40 AND Crowd density front >
       ↪ Crowd density back THEN Go to evacuation exit back
5  IF istrue(Has next node) THEN Walk
6  IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(
       ↪ Memory Global nearest exit) THEN Go to global nearest exit in memory
7  IF istrue(In seat zone) THEN Go to aisle
8  IF istrue(Memory Nearest exit front) THEN Go to nearest exit in memory
9  IF istrue(See evacuation exit) THEN Go to evacuation exit
10 IF istrue(Memory Most familiar exit) THEN Go to most familiar exit in memory
```

Listing 4.7: An improved brain to deal with multi-flow directions. Individuals take flow direction into account for re-routing purposes, without being influenced by their patience levels.

As can be observed, the brain 4.7 introduces a new rule (the rule 3) which indicates that an agent should change its movement direction whenever perceived another agent moving in an opposite direction and no other agent is moving with the same direction in its back.

In this sense, a set of experiments was performed considering three distinct populations: $P1$, $P2$ e $P3$. Despite each population has associated a distinct brain, the personal attributes among different populations follow the same distribution parameters. Therefore, each brain is similar to the brain 4.7, being only modified the rule 5 among different populations. Table 4.6 presents the corresponding behaviour associated to rule 5.

Population	Rule 5
P1	IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(Memory Agent ahead direction) THEN Go to agent ahead direction in memory
P2	IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(Memory Global nearest exit) THEN Go to global nearest exit in memory
P3	IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(Memory Crew member) THEN Go to crew member in memory

TABLE 4.6: Populations considered with different actions when entering into an aisle.

In these simulations, it was considered an equal number of individuals of each population type. So, 60 passengers of each type were randomly distributed over the aircraft seats. Figure 4.16 presents the experiment results for both configurations.

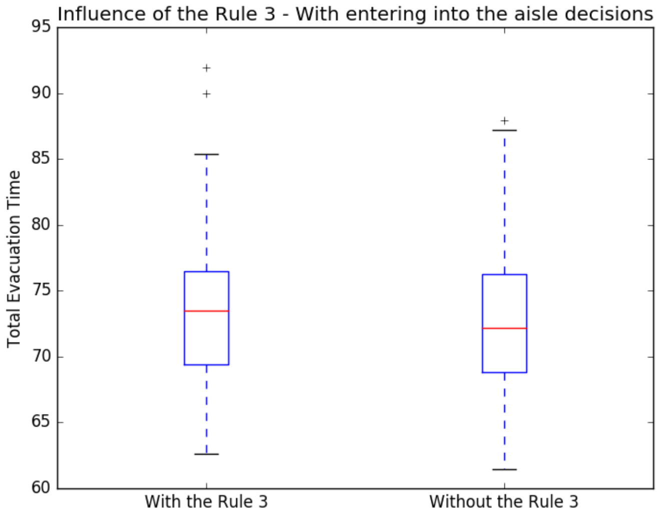


FIGURE 4.16: Results obtained on experiments considering a new rule responsible for deal with multi-flow directions. It is verified that the new rule has no significant influence in the total evacuation time.

Observing Figure 4.16, there is no significant difference in the total evacuation time when considered the new rule of rerouting, being obtained a p-value of 0.309. It can probably be explained by the major influence of the decisions taken when entering into the aisle. Effectively, an organization between passengers is associated to the behaviour identified in the rule 5 of their brains. For example, multi-flows are not expected when passengers are prone to follow the movement direction of their neighbours. Furthermore, they also tend to follow similar routes whenever influenced by the crew member instructions.

In an effort to understand whether these results are directly linked to the decisions taken while entering in the aisle, another set of simulations were executed without considering this behaviour. For this purpose, the rule 5 was discarded from passenger's brain, being only studied whether an absence of the rerouting has a significant influence in the evacuation outcome. Therefore, every passenger chooses their initial route (when exiting their seat zone) according to the last exit perceived, without taking flow direction or crew members instructions into account. Figure 4.17 shows the results obtained in these experiments.

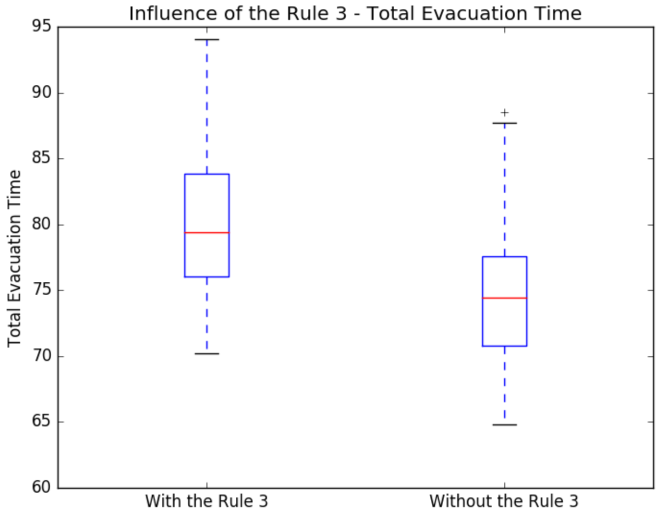


FIGURE 4.17: Results obtained when discarded the decision taken when entering into an aisle.

As can be observed, there is a significant difference between both configurations. Effectively, it was obtained a p-value equals to 3.23×10^{-12}. The rule responsible for rerouting has clearly a major influence on the passengers' behaviour. Through a visual inspection, it is possible to confirm that multi-flow conflicts are resolved more quickly when considered rule 3.

In summary, this new rule is essential to represent human behaviour in these scenarios. It is not correct that rerouting decisions in this situation should be dependent on patience level. Furthermore, it was enhanced that, similarly to real observations, the decisions taken when entering into an aisle have a prominent impact in the egress outcome.

4.7 Patience Level Influence

As discussed in the previous section, a major influence of patience level is expected when this is applied to re-routing purposes. In such circumstances, different behaviour should be observed when modified the patience level of the considered population. Effectively, patience level determines how frequent a passenger leaves its current route and searches for a different one, trying to reduce its personal evacuation time.

In this sense, a set of experiments was conducted with the purpose of understanding how patience level of each passenger can influence the evacuation process as a whole. It was used the same population described in section 4.6, where 60 passengers of each population (with different brains) were randomly seated over the aircraft. Figure 4.18 shows a comparison of total evacuation time between 3 different patience levels: 0.3, 0.6, 0.9.

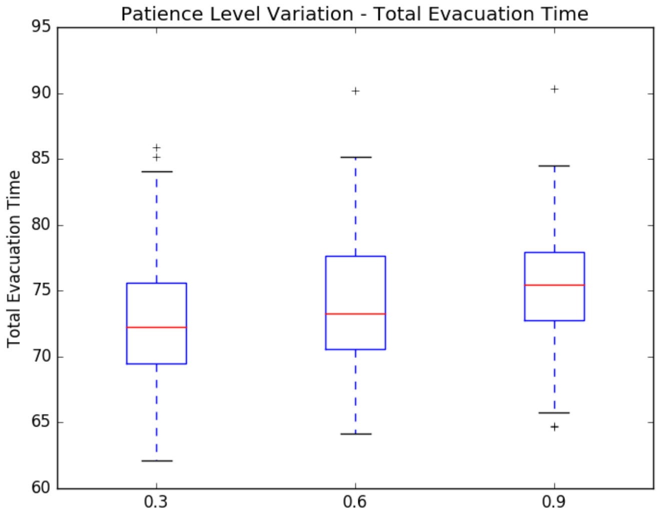


FIGURE 4.18: Results obtained when defined different patience threshold associated to rerouting rules.

In a general manner, it is verified that patience threshold has a major influence on the evacuation process. An increase of the total evacuation time is observed when defined a higher threshold. In this case, several premature re-routing decisions are taken by the passengers, resulting in an increase of their personal evacuation time. On the other hand, a low evacuation time mean is reached when the passengers are more patient and only change their initial routes in critical long waits.

Effectively, these results are in accordance with the behaviour observed in crowd masses scenarios. Many cases in which individuals are subjected to a high level of impatience are associated to disorganization and permanent conflicts. Furthermore, it is required that crew members ensure a considerable patience level among the passengers during the evacuation process. For example, some extreme behaviour, such as seat jumping, may have a negative impact, wherefore crew members try to avoid it.

4.8 Reproduction of Certification Demonstrations

As already refereed, certification scenarios are actually the major focus of this work. After presented and discussed the most interesting components included in the EvacSafeX prototype, some experiments with the purpose of reproducing some certification scenarios found in the literature will be presented in this section.

4.8.1 Certification Cases Description

The following topics will present a description of the two narrow-bodied aircraft configurations considered in these experiments. Both certification scenarios were presented in an extensive report conducted by E. R. Galea et. al. [3], with the purpose of validating *airExodus* simulator while representing this kind of scenarios. However, not all specifications of both considered cases are clear in that report, leading that some of them were imputed according to the most usual values.

Certification Case 1

In this first scenario, it is considered an aircraft with a capacity of 180 passengers and a 3-3 configuration. Therefore, this aircraft is composed of a single central aisle with rows of 3 seats in each side. Four pairs of evacuation exits are considered. Two Type-C exits were positioned at either ends of the cabin enclosure. Two pairs of Type-3 over-wing exits are considered, being accessed by the adjacent seat aisle.

Certification Case 2

For the second scenario, it is considered a narrow-bodied aircraft with a capacity of 162 seated passengers. In total, three pairs of evacuation exits are considered over the aircraft. One pair of Type-C exits is positioned at each end of the cabin. Two Type-3 over-wing exits are accessed through a corresponded seat aisle. Similarly to certification case 1, this aircraft as a 3-3 seat configuration.

4.8.2 Population

Regarding to the population considered in these experiments, it followed the specifications described by the FAA regulation protocol. Therefore, a mix of passengers "in normal health" with a diversity of gender and age was considered. This distinction between individuals was modeled changing some personal attributes already considered in the proposed model, such as response time, maximum walk speed, agility, etc. While some of them were defined according to experiments found in the literature [3], others were assigned following the most suitable representation considered for these specific scenarios. Table 4.7 presents the personal attributes assigned to each population type.

Parameter	Values
Travel speed	Min: 0.8 m/s Max:1.2 m/s
Response time	Mean: 3.93 Min: 0.02 Max: 8.0
Exit delay time	Mean: 1.5 Min: 0.2 Max: 4.0
Vision range	900
Vision angle	175
Vision Reach	50
Find alternative route probability	0.6
Think Probability	10

Table 4.7: Physical and psychological attributes considered for the certification experiments.

Another important aspect of each individual in these experiments is related to its behaviour. The brain rules are responsible for determining the agents' behaviour according to their internal and external perceptions. As already discussed (see sections 4.3 and 4.5), the EvacSafeX model provides a wide range of perceptions and actions, allowing a representation of many different individual's behaviour.

Furthermore, some studies identified the most common behaviour observed in certification scenarios (see section 2.4). In addition, it is also indicated a corresponding percentage of occurrence of each behaviour, based on real observations. In this sense, the brain rules defined for each population type were based on these results in an effort to represent the population diversity observed in these scenarios.

P1 - Passengers significantly influenced by flight attendants' instructions

The majority of the passengers in certification scenarios are receptive to the gestures executed by the flight attendants. They tend to move towards them and follow their instructions. Therefore, an effort to represent a population of individuals which are truly receptive to the flight attendants' instructions, resulted in the brain 4.8.

```
IF istrue(Is ready to exit) THEN Exit
```

```
2   IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 80
      ↪ THEN Stop
3   IF not(In seat zone) AND Agent movement direction front = 0 AND Agent movement
      ↪  direction back < 1 THEN Go to opposite direction
4   IF not(In seat zone) AND Nearest crew member instruction = 0 AND Agent
      ↪ movement direction back < 1 THEN Go to opposite direction
5   IF not(In seat zone) AND Nearest crew member instruction < 0 AND Agent
      ↪ movement direction back < 1 AND Feature Patience < 5 THEN Go to
      ↪ opposite direction
6   IF istrue(Has next node) THEN Walk
7   IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(
      ↪ Memory Crew member) THEN Go to crew member in memory
8   IF istrue(In seat zone) THEN Go to aisle
9   IF istrue(See crew member redirecting) THEN Go to crew member direction
10  IF istrue(See evacuation exit) AND Random number 2 < 30 THEN Go to evacuation
      ↪ exit
11  IF istrue(Memory Nearest exit front) THEN Go to nearest exit in memory
12  IF istrue(Agent ahead direction) THEN Go to agent ahead direction
13  IF istrue(Has direction to forward) THEN Go to direction to forward
```

Listing 4.8: The brain associated to a population with a clear tendency to follow crew members' instructions.

Through a detailed analysis of the brain 4.8, it is verified that several rules are composed of one or more perceptions related to crew members. Initially, a passenger takes a route towards the nearest crew member, among the ones perceived, while leaving the seat zone (see rule 9). Then, it is described that an individual follows the recommended instructions whenever perceived a crew member. Otherwise, a new route will be chosen according to the nearest exit location (in front) or the movement direction of a perceived individual.

Furthermore, some rules placed before the "Walk" action can be observed. As already approached (see section 4.4), these rules are often associated to re-routing scenarios, where individuals may change their current routes due to some external or internal factors. A brief description of each one of these rules is presented next.

The rule 3 represents a major component related to cooperation and organization between passengers. In this case, an individual changes his route whenever perceived another in front moving in an opposite direction. Effectively, through an observation of real certification demonstrations, it is verified that most passengers search for an adjustment of their routes in an attempt to avoid multi-flow direction conflicts.

Regarding to the route taken when entering into an aisle, it is clear that these passengers are mainly influenced by a perceived crew member. They will follow flight attendants' instructions whenever perceived someone while moving from the seat zone to the aisle. Effectively, previous experiments had already shown a major influence of this behaviour in the evacuation process.

Both rules 4 and 5 represent a clear example of how crew members' influence can be represented in the passengers' brain. In this sense, an individual changes its current route whenever perceived a crew member redirecting to an opposite zone in the aircraft. Furthermore, passengers can also change their route when reached a certain patience level, without being perceived any crew member instructions.

P2 - Passengers which follow other individuals

Another considerable slice of passengers in certification scenarios is mainly influenced by the perceived neighbours. Indeed, some individuals have a clear tendency to follow the others around them. The brain 4.9 represents an attempt to reproduce this kind of population.

```
1  IF istrue(Is ready to exit) THEN Exit
2  IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 80
       ↪ THEN Stop
3  IF not(In seat zone) AND Agent movement direction front = 0 AND Agent movement
       ↪  direction back < 1 THEN Go to opposite direction
4  IF not(In seat zone) AND istrue(Agent back direction) AND Agent movement
       ↪ direction back < 1 AND Feature Patience < 40 AND Random number < 70
       ↪ THEN Go to agent back direction
5  IF not(In seat zone) AND istrue(Agent back direction) AND Agent movement
       ↪ direction back < 1 AND Feature Patience < 40 AND Crowd density front >
       ↪ Crowd density back THEN Go to agent back direction
6  IF not(In seat zone) AND Agent movement direction back < 1 AND Feature
       ↪ Patience < 5 AND Random number 4 < 30 THEN Go to opposite direction
7  IF istrue(Has next node) THEN Walk
8  IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(
       ↪ Memory Agent ahead direction) THEN Go to agent ahead direction in
       ↪ memory
9  IF istrue(In seat zone) THEN Go to aisle
10 IF istrue(See crew member redirecting) THEN Go to crew member direction
11 IF istrue(See evacuation exit) AND Random number 2 < 30 THEN Go to evacuation
       ↪ exit
12 IF istrue(Memory Nearest exit front) THEN Go to nearest exit in memory
13 IF istrue(Has direction to forward) THEN Go to direction to forward
```

Listing 4.9: The brain associated to individuals which are mainly influenced by their neighbors.

At a first sight, it is specified that these individuals take an initial route towards the nearest occupant instantly or previously perceived in their front (see the rule 8). Besides, these individuals are attracted by the flight attendants and evacuation exits perceived during the evacuation process.

However, long waits, and consequent influence in the patience level, may lead to some route changes as a way of searching for a faster egress from the cabin. Contrarily to the behaviour represented in the population previously presented, these rerouting initiatives are not influenced by the crew members' instructions. Instead, they are stimulated by the crowd flow directions perceived by the individual. In this sense, the rules 4 and 5 seek to represent a behaviour where an individual proceeds to a route change when reached a certain patience level. Therefore, it only occurs if an individual moving towards an opposite direction is being perceived through the back vision cone.

In addition, it can be observed that both rules 4 and 5 are quite similar. In fact, the main difference between them is related to the influence of the crowd density in the route change's decision. Therefore, it is specified that in 70% of the cases, an individual only changes its route if perceived a smaller amount of passengers in the back vision cone. It is in accordance with the feedback given by several volunteers at the end of certification demonstrations [48].

P3 - Passengers which seek for the nearest exit

The last brain considered in these experiments tries to represent a range of occupants with selfish and goal-oriented characteristics. They have a clear tendency to choose a route by their own instead of following crowd direction or flight attendant's indications. In these sense, they are mainly influenced by their knowledge of the exit locations. An effort to represent this kind of individuals resulted in the brain 4.10.

```
1  IF istrue(Is ready to exit) THEN Exit
2  IF istrue(See prioritary agent) AND not(In seat zone) AND Random number < 80
       ↪ THEN Stop
3  IF not(In seat zone) AND Agent movement direction front = 0 AND Agent movement
       ↪  direction back < 1 THEN Go to opposite direction
4  IF not(In seat zone) AND istrue(See evacuation exit back) AND Agent movement
       ↪ direction back < 1 AND Feature Patience < 40 THEN Go to evacuation exit
       ↪  back
5  IF not(In seat zone) AND Agent movement direction back < 1 AND Feature
       ↪ Patience < 5 AND Random number 4 < 30 THEN Go to opposite direction
6  IF istrue(Has next node) THEN Walk
7  IF istrue(In seat zone) AND istrue(Is entering into an aisle) AND istrue(
       ↪ Memory Global nearest exit) THEN Go to global nearest exit in memory
8  IF istrue(In seat zone) THEN Go to aisle
9  IF istrue(See evacuation exit) AND Random number 2 < 30 THEN Go to evacuation
       ↪ exit
10 IF istrue(Memory Nearest exit front) THEN Go to nearest exit in memory
11 IF istrue(See crew member redirecting) THEN Go to crew member direction
12 IF istrue(Agent ahead direction) THEN Go to agent ahead direction
13 IF istrue(Has direction to forward) THEN Go to direction to forward
```

Listing 4.10: The brain associated to a population with selfish and goal-oriented characteristics.

As described by the rule 3 (see brain 4.10), an individual has a probability of 30% of seeking for the nearest exit within his field of view. However, he tends to seek the nearest one on his front among the ones remembered and recorded in memory. As last resort, these kind of passengers will follow the crew member's instructions.

Regarding to route changes when facing congestions, these individuals are mainly influenced by the evacuation exits perceived during the evacuation process. Through an analysis of the rule 4, it was verified that an occupant changes his route whenever reached a certain patience threshold. Also, this is dependent on what is perceived in the surrounding environment. This rerouting only occurs when an evacuation exit is perceived. Effectively, some real observations of certification scenarios make it possible to conclude that, in general, a rerouting is only proceeded when an individual knows that an alternative exit is available. Therefore, rule 5 indicates that a "blind" rerouting only occurs in 30% of cases, after reached a low patience level.

4.8.3 Experimental Results

Once defined the experimental conditions, a presentation of the results obtained in both certification scenarios will be performed in this section. These results will be compared to real certification and *airExodus* prediction results, for similar scenarios. Each experimental configuration was executed using 100 distinct random seeds in order to obtain a statistical representation of different hypothetical behaviours and distribution of the passengers over the aircraft seats.

4.8.3.1 Certification Case 1

As referred in section 4.8.1, the certification case 1 considers a narrow-bodied aircraft with a capacity of 180 passengers. According to the most common behaviour observed in these scenarios, the previously defined population was distributed over the aircraft according to the following criteria:

- 70% of passengers following P1 specifications
- 20% of passengers following P2 specifications
- 10% of passengers following P3 specifications

When executed these experiments, it was generated a total evacuation time frequency distribution as represented in Figure 4.19. Effectively, it is verified that the real value is higher than the predicted mean value. A *total evacuation time* between 58.24 and 88.72 seconds with a mean value of 69.94 seconds was obtained. In the real evacuation demonstration, it was reached a total evacuation time of 78.5 seconds. Table 4.8 presents a comparison of these results to the predictions generated by the *airExodus* simulator.

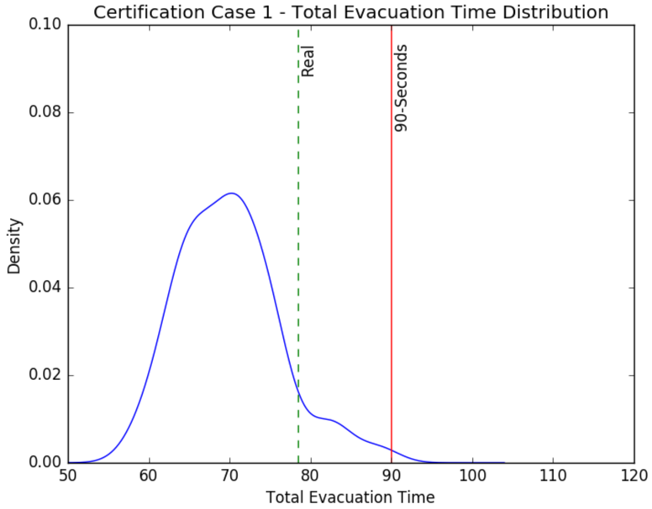


FIGURE 4.19: Frequency distribution generated by the proposed model for the certification case 1.

TABLE 4.8: Results obtained for the certification case 1. It is observed similar total evacuation time predictions in both models.

	TET		CWT		PET		FPO	
	ESX	airExodus	ESX	airExodus	ESX	airExodus	ESX	airExodus
Min	58.2	64.1	11.5	22.7	30.9	35.1	7.6	7.5
Mean	69.9	69.4	14.3	24.6	34.2	37.2	8.1	7.7
Max	88.7	74.8	26.8	24.6	52.3	39.2	9.5	8.7
Stdev	6.18	1.7	1.8	0.7	2.7	0.7	0.3	0.1

† All presented values are expressed in seconds

* ESX - EvacSafeX
* TET - Total Evacuation Time
* CWT - Cumulative Evacuation Time
* PET - Personal Evacuation Time
* FPO - First Person Out

Through the analysis of Table 4.8, it is possible to verify that a similar total evacuation time mean values was obtained when compared to the airExodus prediction. Also, the range for total evacuation time predicted by the airExodus simulator does not include the evacuation time measured in the real certification demonstration (78.5 seconds). In contrast, the EvacSafeX predictions include this real evacuation time, suggesting that similar phenomena to the ones observed in certification scenarios may be well represented in the proposed model.

Other disparities between results are observed in the cumulative wait time. It can be associated to distinct navigation methodologies applied by each model. Contrarily to the airExodus simulator, the proposed model considers a movement in a continuous space. In this way, every step (even the shortest one) is considered, not providing a contribute to the cumulative wait time of a given. In contrast, a passenger can only move to the next node when it becomes free. Effectively, when looking at personal evacuation time metric, similar mean values were obtained. It clearly indicates that, in general, similar waiting times are being predicted in both models.

Still on the personal evacuation time, it is verified a higher maximum value due to a wrong rerouting decision taken by a set of occupants. Indeed, a visual observation makes it clear that some occupants decided to move towards a different evacuation exit, either because they reached their patience level, or perceived another individual following that direction.

4.8.3.2 Certification Case 2

Regarding to the certification case 2, it considers a narrow-bodied aircraft with 150 seated places. The population was distributed in a similar way of the one considered in the certification case 1:

- 70% of passengers following P1 specifications
- 20% of passengers following P2 specifications
- 10% of passengers following P3 specifications

In this way, Figure 4.20 represents the total evacuation time frequency distribution predicted by the *EvacSafeX* model. It was generated a total evacuation time between 54.8 and 81.0 seconds, with an average value of 65.86. Comparing to the egress time obtained in the real certification, the predicted value is 1.76 seconds higher. Also, the real value is within the range of total evacuation time generated by the proposed model. Table 4.9 shows a comparison of the results obtained using the *EvacSafeX* and *airExodus*, for similar conditions.

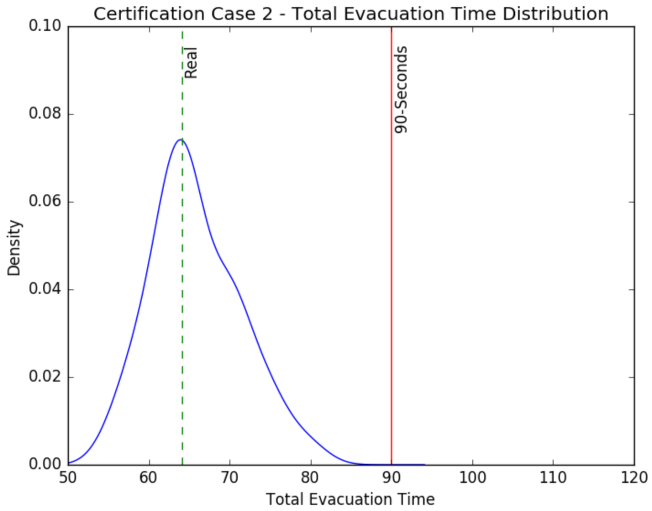


FIGURE 4.20: Frequency distribution generated by the proposed model for the certification case 2.

TABLE 4.9: Results obtained for the certification case 2. It is shown a comparison between predictions generated by *EvacSafeX* and *airExodus*. Similar interesting results are observed when comparing both models.

	TET		CWT		PET		FPO	
	ESX	airExodus	ESX	airExodus	ESX	airExodus	ESX	airExodus
Min	54.8	59.8	11.5	20.4	29.9	33.3	7.6	7.5
Mean	65.9	65.0	13.7	22.6	33.4	35.7	8.2	7.7
Max	81.0	77.4	16.75	24.7	38.0	37.8	9.6	8.9
Stdev	5.6	2.1	1.35	0.7	1.8	0.7	0.3	0.1

† All presented values are expressed in seconds

* ESX - EvacSafeX
* TET - Total Evacuation Time
* CWT - Cumulative Evacuation Time
* PET - Personal Evacuation Time
* FPO - First Person Out

Observing the Table 4.9, it is verified that both models predicted similar total evacuation time mean values. However, the *EvacSafeX* model presented a higher standard deviation on this metric. It may have occurred due to different initial conditions being considered. The experiments conducted with the *EvacSafeX* model assumed different random values and distinct distributions of passengers over the aircraft in each run. In the *airExodus* experiments, there is not a clear explanation about these aspects.

Regarding to the cumulative wait time, the observed disparities may have occurred due to the same reason already explained for the certification case 1. Also, similar personal evacuation time values were predicted by both models, suggesting that the EvacSafeX model is performing a right representation of the passengers' behaviour in certification scenarios. Also, a visual inspection of some runs indicates an interesting emergent behaviour, representative of the ones observed in these scenarios.

Chapter 5

Conclusion

In this chapter, a general discussion on the outcome of this work, as well as its main contributions, will be performed. Also, some proposals of future work will be presented.

5.1 General Discussion

The main goal of this work has been to look for an approach based on complex systems and multi-agent systems to simulate aircraft evacuation scenarios. The EvacSafeX was presented and has been under development as an effort to combine airExodus components in a decentralized system. It is desired an emergence of complex interactions between passengers through a definition of individual faculties. Therefore, the model is centered on each passenger individually instead of on the system as a whole. These characteristics form the basis of BitBang framework, taking that the proposed model is being developed according to the BitBang's architecture.

Human behaviour is consequently a main focus in this research. Understanding human behaviour in aircraft evacuation scenarios has been essential to define which components have a major influence, such as perceptions, actions and the decision process inherent to them. In this sense, the EvacSafeX architecture was thought to provide a wide range of components to represent human behaviour in these scenarios. Also, a flexible architecture has been attempted to be designed, in which more components may easily be incorporated into the system. In this sense, some abstract components are available in the proposed model, and can be extended to include other ones with more specific characteristics.

Actually, a set of features is already included in the proposed model, taking certification scenarios as the main focus. These were essentially obtained through an inspection of video recordings and an analysis of other works which identifies the most common decisions taken in these situations. An iterative process is being adopted with the purpose of incorporating and validating these human behaviour components. Furthermore, a forward chaining inference mechanism was applied to the rule list brain. Through several experiments, it has proven to be able to represent a wide range of distinct behaviour.

The validation process has only been possible due to the implementation of the EvacSafeX prototype. Undoubtedly, it constitutes a considerable part of this work, providing a credible observation of the system behaviour and a comparison of these observations with the real ones. Its graphical and physical engines are undeniably major components for an appropriate validation. Therefore, it is desired that all the components considered in the model can be implemented and validated in the prototype.

An important step of the validation process has resorted to some real certification scenarios also approached by the airExodus model. The predictions provided by the EvacSafeX were compared to the ones presented by the airExodus in an effort to understand whether the proposed model is performing an accurate representation of aircraft evacuation scenarios. Effectively, the obtained results are very promising. It was verified that many of them match the ones predicted by the airExodus model.

Furthermore, a visual inspection of the entire simulation is probably the most important validation mechanism. The EvacSafeX validation process was conducted with a permanent visual inspection of the simulation progress. In general, several interesting emergent phenomena were verified in the experiments, clearly indicating that the proposed approach is able to deal with aircraft evacuation scenarios.

Once crew members take effectively a major role in these scenarios, they are not forgotten in the proposed model. An initial representation of these individuals is already included, with a special focus on their roles in certification scenarios. Specifically, they are responsible for conducting and encouraging passengers during their egress in order to speed up the evacuation process.

Another aspect approached in this work is related to the navigation mechanism. As referred, a pre-built graph structure is being used to support agents' navigation over the aircraft. Some different aircraft layouts were tested in the proposed model as a way of validating the graph generation algorithm. In a general manner, the proposed algorithm is able to generate a graph structure with a right representation of the navigable space. On the other side, some paths with an uninteresting configuration are generated when defined a more complex aircraft architecture. However, it is clear that these issues can be easily filled through an adjustment of some nodes' positions. Effectively, an interactive graphical interface can be seen as the better way to easily perform these small refinements on the navigation graph.

Computational performance aspects have also not been discarded from the proposed model. In this way, a spatial partition algorithm was implemented in an attempt to reduce computational effort associated to the collision detection process. Although it is not being presented a study on this mechanism's influence, some ad-hoc experiments identified an obvious influence on the simulator performance. Effectively, a simulation environment with many dynamic objects could suffer from some performance issues, if not considered the implemented mechanism.

5.2 Future Work

While this work has demonstrated the potential of simulating aircraft evacuation scenarios, many issues and opportunities for extending the scope of the EvacSafeX model deserve further study. In this way, the most important ones are presented in this section.

As discussed in section 5, some issues were verified in the graph generation algorithm. Effectively, in some cases it is needed an adjustment of the position of some nodes. Also, aircraft layout is actually built through a configuration file. To tackle both issues, an interactive graphical interface is effectively the best solution. In this way, an user should be able build an aircraft layout and perform changes on the generated graph in an interactive manner.

For validation purposes, only two distinct certification cases were considered. Despite the promising results obtained in both scenarios, several different ones should be considered in order to achieve a better validation of the proposed model. Therefore, other simulations considering a wider range of aircraft configurations are truly important to enrich the model and make it more credible.

Apart from the certification scenarios, real world aspects have a major importance on the simulation of aircraft evacuation. It is known that there are many differences between the occupants' behaviour when compared certification to real world scenarios. In this way, further development of these cases should be focused on an incorporation of new components (perceptions, actions, etc.) which represent them in the model. Also, an extension of the proposed model should consider bonding aspects. Effectively, in real world world scenarios, several passengers are physically or emotionally connected, which might influence their egress.

Another point which deserves further attention is related to the flight attendants' representation. More interactions and information sharing between these entities are identified as being crucial in the evacuation outcome. In this sense, an extension of the initial crew member's representation should be a next step, wherefore new perceptions and actions will be incorporated in an attempt to obtain a better representation of their roles in evacuation scenarios.

Appendix A

Project Planning

In this chapter, it will be presented a description of the development methodology adopted along this project as well as the main deviations from the initial plan. Effectively, some changes was performed on some aspects in an attempt to follow the recommendations received during the intermediate defense.

Regarding to the scope of the presented work, it focused only on certification evacuation scenarios. Therefore, human representation and aircraft conditions are actually incorporated taking certification as the main focus. Therefore, real evacuation scenarios are intended to be represented in a further development iteration on the proposed model.

Once this is a research project, scientific method is strongly associated with it. Definitely, there is a high exploration component, wherefore it should be considered changes on the requirements. However, a more formal development methodology was defined and has been adopted. The methodology adopted is an adaptation of waterfall model, assuming a more flexible process than the unmodified waterfall model. In contrast to unmodified waterfall model, the one adopted in this project allows a return to a previous stage in some specific cases. Figure A.1 shows all the considered stages and their corresponded transitions.

As described in Figure A.1, an improvement of model's architecture is considered after both implementation and validation processes. Effectively, in exploration projects some components might prove to be inadequate in the model while they are being implemented. Also, an emergence of new interesting features can be observed during implementation stage. In both situations, an improvement of some architecture aspects may be needed. Also, finished a given set of validation experiments, some new aspects can arise as being important to be considered in the model, leading to an hypothetical

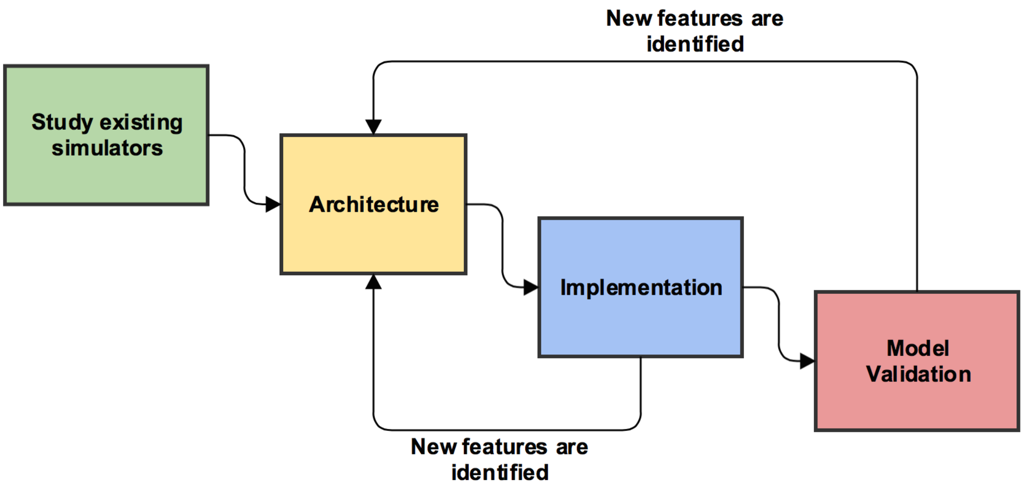


FIGURE A.1: Project development methodology

redefinition of the architecture. However, it is important to make clear that a base architecture is already defined (see chapter 3) and the redefinition mentioned before consist in an improvement of model's complexity and quality while representing real aircraft evacuation scenarios.

The initial plan defined in the begging of the project considered the following stages and corresponding sequence order:

- First Semester
    1. Study of airExodus Model
    2. Study of BitBang Framework
    3. Architecture Definition
- Second Semester
    4. Prototype Implementation
    5. Experiments Setup
    6. Experiments Analysis
    7. Model Extension
    8. Implementation of New Features
    9. Definition of New Experiments
    10. Experiments Analysis

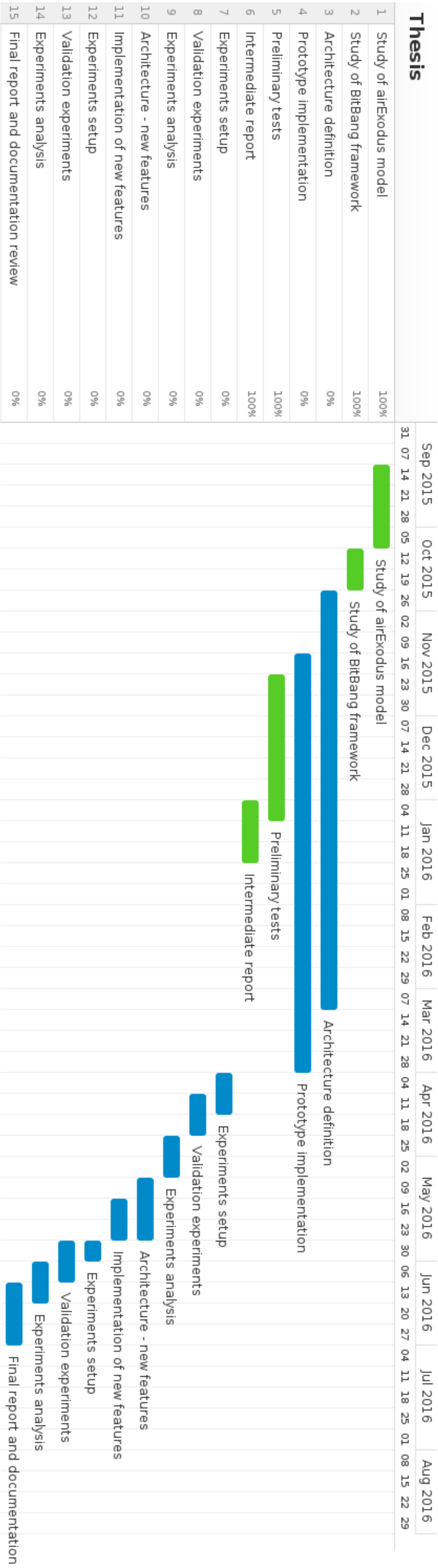
Nevertheless, this initial plan was modified during the first semester due to the adoption of the methodology already referenced. So, both architecture and prototype implementation were performed at the same time (see Figure A.1). Initially, an architecture based on BitBang specifications was defined and more components were being integrated in the prototype, improving its complexity. This methodology is considered the most suitable given that it allows an integration of new components (e.g. actions, perceptions etc) with a continuous feedback about its influence on the model.

An overview of the work plan expected at the begging of this project is represented in Figure A.2, though a Gantt diagram.

Indeed, some architecture aspects were modified after the intermediate defense. For instance, human behaviour mechanism was initially defined with a rigid separation between rational and instictive behaviour. In this way, brain rules were intended to an exclusive representation of the rational component. Instead, all the complexity related to the human behaviour could make it difficult to distinguish between rational or instinctive. Therefore, all the perceptions, actions and inference mechanism were thought to provide a flexible and proper representation of the human behaviour in evacuation scenarios without an separation criteria.

Furthermore, validation process focused initially on an sensitivity analysis of some core parameters as a way of understand whether the emergent behaviour is in accordance with the ones observed in real cases. This validation stage was also important to build agents' brain and reach the most suitable representation of the human behaviour. Later, some real certification scenarios were considered and represented in the proposed model. The evacuation results were analyzed and compared to the airExodus predictions with the purpose of validate EvacSafeX while representing these certification cases.

A continuous updating of the final report was also being performed along this semester. In this way, validation experiments were also executed after finishing a description of the architecture. However, some experiments lead to a modification of some components and consequent updating of the report.



Thesis

1	Study of airExodus model	100%
2	Study of BitBang framework	100%
3	Architecture definition	0%
4	Prototype implementation	0%
5	Preliminary tests	100%
6	Intermediate report	100%
7	Experiments setup	0%
8	Validation experiments	0%
9	Experiments analysis	0%
10	Architecture - new features	0%
11	Implementation of new features	0%
12	Experiments setup	0%
13	Validation experiments	0%
14	Experiments analysis	0%
15	Final report and documentation review	0%

Figure A.2: Gantt diagram

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