ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΛΟΠΟΝΝΗΣΟΥ
Σχολή Οικονομίας και Τεχνολογίας
Τμήμα Πληροφορικής και Τηλεπικοινωνιών

Διδακτορική Διατριβή

Μηχανές Παιγνίων για την αξιολόγηση Σχεδιασμού και την Εκπαίδευση σε θέματα Ασφάλειας

Game Engines for Assessment and Safety Training

Γεωργιος Κουγιουμτζογλου

Τριπολη, 2022

Defence Committee

George Lepouras, Professor, Department of Informatics and Telecommunications, University of Peloponnese (Supervisor).

Anastasios Theodoropoulos, Assistant Professor, Department of Informatics and Telecommunications, University of Peloponnese (Member of steering committee)

Nikolaos Platis, Assistant Professor, Department of Informatics and Telecommunications, University of Peloponnese (Member of steering committee).

Vassilios Poulopoulos, Assistant Professor, Department of Informatics and Telecommunications, University of Peloponnese

Konstantinos Vassilakis, Professor, Department of Informatics and Telecommunications, University of Peloponnese

Aggeliki Antoniou, Assistant Professor, Department of Informatics and Telecommunications, University of Peloponnese

Vassilios Drakopoulos, Associate Professor, Department of Computer Science and Biomedical Informatics, University of Thessali.

This page was intentionally left blank

Abstract

The safe evacuation of passenger ships is a major issue for the marine industry. Methods such as Evacuation Drills and Simulations have been tested. They may provide reliable data, but their insufficient repeatability, their excessive cost, and their duration, reduces their value (Klüpfel et al., 2001; Johnson, 2006). Nevertheless, the evacuation drills provide reliable results, involving humans as evacuees, while introducing the Human Behavior into the evacuation process. To overcome some of the previously mentioned issues, computerized Serious Games Evacuation Simulators have been proposed, although they usually do not allow the participation of human evacuees and their focus is the validation of existing models and safety standards, as well as the definition of the evacuation processes. This problem has been overcome with the development of 3D evacuation simulators, but most of them lack authentic human behavior in dangerous situations. In this work, it is proposed to alleviate these shortcomings by training the evacuees, and in this case the passenger of liner ships, by using the Unreal 4 Game Engine to develop a 3D Multiplayer Gamified Ship Evacuation Serious Game/Simulator with the name Ship Evacuation Simulator (SES). On top of the 3D multiplayer environment, the simultaneous participation of computer-controlled (bots) and human-controlled evacuees is implemented while Gamification and Edutainment principles are introduced, to motivate and immerse the users in the virtual environment and behave similarly to real evacuees. The model that implements Human Behavior, to the computer-controlled bots, is a combination of the Affiliation and the Protective Action Decision Models, whereas the Models that implement their movement are AI-based. The simulation sessions are conducted in a fully three-dimensional environment under the supervision of an administrator, while the users join as evacuees. An administrator sets up the options of every session and can intervene in real-time, spawning elements and events or changing variables of the simulation. SES constitutes a lightweight and flexible prototype framework for testing Passenger Ships on safety standards and for training purposes, which may be easily implemented to different ship types with minimal modifications, as a novel approach focused primarily on the particularities of Greek shipping, whereas it can be applied to any environment. This work is aspires to evaluate the Game Engines as development environments for the development of Evacuation Simulators, to validate the results by comparing the results of SES with real evacuation incidents and other experimental data, to estimate the effects of the concurrent participation of human players with computer-controlled bots, and to assess the application of SES to the marine industry, towards the training of passenger and the improvement of safety in sea travel, increasing the repeatability of the serious games/simulations, while maintaining a degree of realistic behavior.

Αφορμή για την παρούσα έρευνα ήταν τα καταστροφικά ατυχήματα του Express Samina Papanikolaou et al., 2004), του Costa Concordia (Giustiniano et al., 2016; Schröder-Hinrichs et al., 2012) και το Norman Atlantic (Vairo et al., 2017). Η ραγδαία ανάπτυξη της τουριστικού τομέα στην Ελλάδα, όπου επικεντρώνεται κυρίως σε νησιωτικές και παραθαλάσσιες περιοχές, οδήγησε σε έναν αριθμό ατυχημάτων σχετιζόμενα με αυτόν το τομέα. Σκοπός της ανάπτυξης του SES είναι η ανάπτυξη ενός Εξομοιωτή Εκκένωσης για βελτίωση της σχεδίασης και των κανόνων εκκένωσης, τον έλεγχο ασφάλειας την επιβατικών πλοίων και την εκπαίδευση πληρωμάτων και σωστικών συνεργείων.

Η έρευνα αρχίζει με την αξιολόγηση υπαρχόντων μοντέλων κίνησης και συμπεριφοράς, υπό το πρίσμα υπαρχόντων εξομοιωτών εκκένωσης. Διαπιστώνεται ότι υπάρχει μία πολυετής προσπάθεια ανάπτυξης εξομοιωτών, αλλά τα τελευταία χρόνια έχει προχωρήσει η ανάπτυξη τρισδιάστατων εξομοιωτών, όπως το VELOS και το EVA. Με βάση τα παραπάνω δεδομένα τίθενται τα Ερευνητικά Ερωτήματα της

εργασίας. Θα μπορούσαν τα στοιχεία συμπεριφοράς και κίνησης να συνδυαστούν σε προσομοιωτή εκκένωσης; Ποιος είναι ο αντίκτυπος της εισαγωγής ανθρώπινων χρηστών σε ηλεκτρονικούς προσομοιωτές εκκένωσης; Ποιος είναι ο αντίκτυπος της ταυτόχρονης συμμετοχής ανθρώπινων χρηστών και bots που ελέγχονται από υπολογιστή; Μπορεί να αυξήσει τον ρεαλισμό και να παρέχει επικυρωμένα αποτελέσματα; Πώς μπορούμε να παρακινήσουμε τους ανθρώπους-συμμετέχοντες να αντιδρούν ρεαλιστικά; Θα μπορούσε η εφαρμογή του Gamification να εφαρμοστεί στο πεδίο της προσομοίωσης εκκένωσης;

Βασισμένη πάνω στα Ερευνητικά Ερωτήματα, η έρευνα αξιολογεί την δυνατότητα μοντελοποίησης στοιχείων και φαινομένων, που παρατηρούνται σε εκκενώσεις χώρων, όπως και παραγόντων εκκένωσης και εφαρμογής του Gamification. Αφού έχει εκτιμηθεί ότι είναι δυνατή η μαθηματική μοντελοποίηση των παραπάνω παραγόντων, μπορούν να ενσωματωθούν σε εφαρμογές και συνεπώς σε αλγορίθμους. Επομένως, στην συνέχεια περιγράφεται η μέθοδος ανάπτυξης εξομοιωτών εκκένωσης και οι παράγοντες και τα στοιχεία που πρέπει να περιληφθούν. Αφού περιγράφεται η μοντελοποίηση των φαινομένων εκκένωσης και η δυνατότητα ανάπτυξης με την χρήση Μηχανών Παιχνιδιών (Games Engines), περιγράφεται η ανάπτυξη του SES, με τα χαρακτηριστικά που περιγράφονται παραπάνω. Τα συμπεράσματα περιγράφουν τα αποτελέσματα των πειραματικών δοκιμών στον εξομοιωτή και την συζήτηση πάνω στην δυνατότητα των Game Engines, για την ανάπτυξη Εξομοιωτών Εκκένωσης και στην δυνατότητα της συμμετοχής ανθρώπων σε εικονικές εκκενώσεις χώρων και την δυνατότητα της εφαρμογής να εκπαιδεύσει τους συμμετέχοντας και αυτό να επαναληφθεί πολλές φορές (Επαναληψιμότητα).

The study initially evaluates motion and behavior models in existing evacuation simulators. It is noted that there is a multi-year effort to develop simulators, but in recent years, there is a new dynamic with the development of 3D simulators, such as the VELOS and the EVA. Based on the above data, the Research Questions of the paper are posed.

Could behavioral and movement elements be combined in an evacuation simulator? What is the impact of introducing human users into computerized evacuation simulators? What is the impact of the simultaneous participation of human users and computer-controlled bots? Could this increase realism and provide validated results? How could we motivate human participants to react realistically? Could Gamification be applied to the field of evacuation simulation?

Based on the above Research Questions, this study evaluates the capability of modeling elements and phenomena observed in space evacuations, as well as evacuation factors and the application of Gamification. Once it is proven, that mathematical modeling, of the above-mentioned factors is possible, they can be integrated into applications and therefore into algorithms. Therefore, the method of developing discharge simulators and the factors and elements that should be included are described below. After describing the modeling of evacuation phenomena and the possibility of development using Games Engines, the development of SES is described. The conclusions describe the results of the experimental tests on the simulator and the discussion on the capabilities of Game Engines, for the development of Evacuation Simulators, the potential participation of human testers in virtual evacuations and the ability to train the participants how easily this could be repeated multiple times (Repeatability).

Εκτεταμένη Περίληψη

Η αξιολόγηση της ασφάλειας των επιβατηγών πλοίων αποτελεί ένα από τα μείζονα ζητήματα για τις θαλάσσιες συγκοινωνίες. Μέθοδοι όπως οι προσομοιώσεις έχουν δοκιμαστεί στο παρελθόν, αλλά ενώ μπορεί να παρέχουν αξιόπιστα αποτελέσματα, λόγω της ανεπαρκούς επαναληψιμότητας τους, το υπερβολικό κόστος και την μεγάλη τους χρονική διάρκεια τους, υποβαθμίζει την αξία τους (Klüpfel et al., 2001; Johnson, 2006). Ωστόσο, οι ασκήσεις εκκένωσης παρέχουν αξιόπιστα αποτελέσματα καθώς επιτρέπουν την εμπλοκή ανθρώπων στην διαδικασία της εκκένωσης, εισάγοντας το στοιχείο της Ανθρώπινης Συμπεριφοράς. Για να ξεπεραστούν ορισμένα από τα προαναφερθέντα ζητήματα, έχουν προταθεί η ανάπτυξη Σοβαρών Παιγνίων/Προσομοιωτών εκκένωσης, αν και συνήθως δεν επιτρέπουν τη συμμετοχή ανθρώπων, ειδικά αν κοιτάξουμε τις εφαρμογές δισδιάστατων γραφικών. Αυτό το πρόβλημα έχει επιλυθεί εν μέρει με την ανάπτυξη Σοβαρών Παιγνίων/Προσομοιωτών εκκένωσης 3D, αλλά οι περισσότεροι από αυτούς δεν καταφέρνουν ή ενδιαφέρονται να ενσωματώσουν την αυθεντική ανθρώπινη συμπεριφορά σε επικίνδυνες καταστάσεις, πάνω σε bots που ελέγχονται από την εφαρμογή, ειδικά αν μελετήσουμε Δισδιάστατες εφαρμογές. Σε αυτήν την εργασία, προτείνεται να μετριαστούν ή εκμηδενιστούν αυτά τα μειονεκτήματα, εκπαιδεύοντας του επιβάτες επιβατικών πλοίων χρησιμοποιώντας την Unreal Game Engine για την ανάπτυξη ενός 3D Multiplayer Gamified Ship Evacuation Serious Game/Simulation (Ship Evacuation Simulator). Πέρα από το περιβάλλον πολλαπλών παικτών 3D, εφαρμόζεται η ταυτόχρονη συμμετοχή ελεγχόμενων από υπολογιστή (bots) και bots ελεγχόμενων από τον άνθρωπο και εισάγονται τα στοιχεία Gamification, για να παρακινήσουν και να "βυθίσουν" τους χρήστες στο εικονικό περιβάλλον, ώστε να συμπεριφέρονται φυσικά. Το μοντέλο που εφαρμόζει την Ανθρώπινη Συμπεριφορά είναι ένας συνδυασμός των Μοντέλων Αποφάσεων και Προστατευτικής Δράσης και των Μοντέλων που εφαρμόζουν την κίνηση των εξομοιωτών εκκένωσης βασισμένα στην Τεχνητή Νοημοσύνη. Οι συνεδρίες προσομοίωσης διεξάγονται σε ένα πλήρως τρισδιάστατο περιβάλλον υπό την επίβλεψη ενός διαχειριστή, ενώ οι χρήστες συμμετέχουν ως παίκτες. Ένας διαχειριστής ορίζει τις επιλογές κάθε προσομοίωσης και μπορεί να παρέμβει σε πραγματικό χρόνο, αναπαράγοντας στοιχεία και συμβάντα ή αλλάζοντας τις μεταβλητές της προσομοίωσης. Το SES αποτελεί ένα υπολογιστικά ελαφρύ και ευέλικτο πρωτότυπο για τη δοκιμή Επιβατηγών Πλοίων πάνω σε πρότυπα ασφάλειας και για εκπαιδευτικούς σκοπούς, με σκοπό την εκπαίδευση των επιβατών σε καταστάσεις εκκένωσης, αυξάνοντας την επαναληψιμότητα των εξομοιώσεων και διατηρώντας την ρεαλιστική συμπεριφορά των συμμετεχόντων.

Αφορμή για την παρούσα έρευνα ήταν τα καταστροφικά ατυχήματα του Express Samina Papanikolaou et al., 2004), του Costa Concordia (Giustiniano et al., 2016; Schröder-Hinrichs et al., 2012) και το Norman Atlantic (Vairo et al., 2017). Η ραγδαία ανάπτυξη της τουριστικού τομέα στην Ελλάδα, όπου επικεντρώνεται κυρίως σε νησιωτικές και παραθαλάσσιες περιοχές, οδήγησε σε έναν αριθμό ατυχημάτων σχετιζόμενα με αυτόν το τομέα. Σκοπός της ανάπτυξης του SES είναι η ανάπτυξη ενός Εξομοιωτή Εκκένωσης για βελτίωση της σχεδίασης και των κανόνων εκκένωσης, τον έλεγχο ασφάλειας την επιβατικών πλοίων και την εκπαίδευση πληρωμάτων και σωστικών συνεργείων.

Η έρευνα αρχίζει με την αξιολόγηση υπαρχόντων μοντέλων κίνησης και συμπεριφοράς, υπό το πρίσμα υπαρχόντων εξομοιωτών εκκένωσης. Διαπιστώνεται ότι υπάρχει μία πολυετής προσπάθεια ανάπτυξης εξομοιωτών, αλλά τα τελευταία χρόνια έχει προχωρήσει η ανάπτυξη τρισδιάστατων εξομοιωτών, όπως το VELOS και το EVA. Με βάση τα παραπάνω δεδομένα τίθενται τα Ερευνητικά Ερωτήματα της εργασίας. Θα μπορούσαν τα στοιχεία συμπεριφοράς και κίνησης να συνδυαστούν σε προσομοιωτή εκκένωσης; Ποιος είναι ο αντίκτυπος της εισαγωγής ανθρώπινων χρηστών σε ηλεκτρονικούς προσομοιωτές εκκένωσης; Ποιος είναι ο αντίκτυπος της ταυτόχρονης συμμετοχής ανθρώπινων χρηστών και bots που ελέγχονται από υπολογιστή; Μπορεί να αυξήσει τον ρεαλισμό και να παρέχει επικυρωμένα αποτελέσματα; Πώς μπορούμε να παρακινήσουμε τους ανθρώπους-συμμετέχοντες να αντιδρούν ρεαλιστικά; Θα μπορούσε η εφαρμογή του Gamification να εφαρμοστεί στο πεδίο της προσομοίωσης εκκένωσης;

Βασισμένη πάνω στα Ερευνητικά Ερωτήματα, η έρευνα αξιολογεί την δυνατότητα μοντελοποίησης στοιχείων και φαινομένων, που παρατηρούνται σε εκκενώσεις χώρων, όπως και παραγόντων εκκένωσης και εφαρμογής του Gamification. Αφού έχει εκτιμηθεί ότι είναι δυνατή η μαθηματική μοντελοποίηση των παραπάνω παραγόντων, μπορούν να ενσωματωθούν σε εφαρμογές και συνεπώς σε αλγορίθμους. Επομένως, στην συνέχεια περιγράφεται η μέθοδος ανάπτυξης εξομοιωτών εκκένωσης και οι παράγοντες και τα στοιχεία που πρέπει να περιληφθούν. Αφού περιγράφεται η μοντελοποίηση των φαινομένων εκκένωσης και η δυνατότητα ανάπτυξης με την χρήση Μηχανών Παιχνιδιών (Games Engines), περιγράφεται η ανάπτυξη του SES, με τα χαρακτηριστικά που περιγράφονται παραπάνω. Τα συμπεράσματα περιγράφουν τα αποτελέσματα των πειραματικών δοκιμών στον εξομοιωτή και την συζήτηση πάνω στην δυνατότητα των Game Engines, για την ανάπτυξη Εξομοιωτών Εκκένωσης και στην δυνατότητα της συμμετοχής ανθρώπων σε εικονικές εκκενώσεις χώρων και την δυνατότητα της εφαρμογής να εκπαιδεύσει τους συμμετέχοντας και αυτό να επαναληφθεί πολλές φορές (Επαναληψιμότητα).

Acknowledgements

I would like to acknowledge and thank my supervisor Dr. George Lepouras, for his guidance and advice, during the entirety of this PhD. His experience and expertise helped me overcome difficulties, that would have been impossible to alleviate. He gave me the freedom to experiment and explore the topic and to modify any aspect that was compatible with our goals.

I would also like to acknowledge and thank Dr. Anastasios Theodoropoulos, for his constant support and contribution during the research stage of this work. Without Dr. Theodoropoulos the completion of the research would have been impossible. Dr. Theodoropoulos guided me through many hardships, which were resolved with his methodical and scientific approach.

Special thanks to my wife Angelica Antonakis and my family for their constant support during the years of my research. I appreciate their understanding and patience. They helped me keep my mind straight and with their fun and alternative point of view, made the hardships seem easy. During this research, my family increased by one member, and everything changed, but with their support everything was manageable.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(George Kougioumtzoglou)

To Angelica, Ioli and Valeria

Table of Contents

List of Figures

List of Tables

PART I – INTRODUCTION

Chapter 1

1.1 Introduction

Nobody expects to be in a disaster, whereas Human history demonstrates numerous disasters, due to physical phenomena (natural causes) or incidents instigated by humans (anthropogenic causes). The instinct, after the outbreak of a disaster, drives us to some of the most common reactions of human beings, even if these reactions are not in line with the safety standards. The first typical reaction is to protect ourselves and then, if possible, to escape from the affected area, with our relatives and friends. This instinct, supported by other factors, though, while common to humans and animals, has caused numerous evacuation disasters. These evacuations total a high number of casualties, not only due to the incident's severity but, because of the evacuation process itself, which contributed to the casualties (Zhen et al., 2008; Helbing & Mukerji, 2012). Taking such incidents into consideration, we conclude that the evacuation is an extremely dangerous process. We can imagine how risky a considerably large crowd of people, running through the corridors of a building or a passenger ship, stampeding on others, under low or no light conditions, could be. An evacuation process that has not been designed and executed properly, may result in more casualties than the initial event. On the other hand, regardless of the evacuation's planning, during a real incident the egress will be performed by untrained amateurs, children, elder people etc. Hand-on examples of evacuations that went wrong have been evacuation incidents such as The Chicago Iroquois Theatre fire (1903, 602 casualties), the Lakeview Elementary School Fire (1908, 176 casualties), and the Cleveland Clinic Fire (1929, 121 casualties) (Layton & Elhauge, 1982), only in the USA, proving the untrained and unaware crowd cannot evacuate any place, without a high and unnecessary rate of fatalities. Such notable incidents can also be found elsewhere, such as the Sunderland (1883) and the Glasgow (1902) (Dickie,1995) disasters. All the previously mentioned catastrophes have a common pattern. The high volume of people crowded in small spaces or structures; crowds composed mainly of children, families, elders, or handicapped people; primitive, inadequate, or no evacuation plans. The coexistence of these three elements is called *Assured Disaster Conditions (ADC)* and creates the ideal conditions for major disasters. Although, the ADC is not the prominent contributor to the casualties, due to the low number or total absence of underaged children or elderly people, to other famous disasters such as the World Trade Center disaster (Simon & Teperman, 2001) and the Gothenborg Discotheque Fire (1998) (Cassuto & Tarnow, 2003), other elements such as congestion, blocked exits, or hazardous materials, ascended significantly increasing the casualties. Combining the ADC with a severe incident such as a fire or a chemical leakage may end up in a disaster with high casualties.

While we cannot avoid the disaster altogether, we could decrease their impact and subsequently the casualties. Safety standards have been developed for a collection of causes and structures, modeling the data, and setting rules (Ronchi, 2021). A common method to create or improve safety standards is the conduction of controlled evacuation drills. Those are usually motivated by real evacuation incidents and more specifically their causes, their setting, the composition of the crowds of people (Kougioumtzoglou et al., 2021). Other evacuation drills do not use an existing context but attempt to simulate hypothetical scenarios (Manion & Golden, 2004) or experimental data. This approach, although valuable, comes with many flaws and shortcomings, which are discussed below. A novel approach is the development of Evacuation Simulators and Serious Games, which remove many of the drawbacks of an evacuation egress adding up unlimited repeatability. This approach is discussed and assessed in this work, attempting to improve existing models and practices, while proposing innovative features from the perspective of Gamification.

1.2 Research Motivation

One of the most common places where the ADC can be frequently met is a Passenger Liner Ship. A floating platform with limited space and no places to escape, packed with families, elders, and regularly, patients, who travel to or from a hospital (especially, in Greece where most of its islands lack a reliable hospital), filled with fuel from the ship's tanks and the transferred vehicles. Two out of the three conditions have been already in place, coupled with the hazardous materials and the isolation. The evacuation of large passenger ships such as cruises is one of the most complicated processes (Wang et al., 2014). Those factors transform the evacuation of a passenger ship into a unique and individual evacuation subject, completely distinct and with numerous differences, compared to the evacuation of buildings or other structures and vehicles (Guarin et al., 2004).

The most profound way to avoid naval disasters, such as General Slocum (1904, 1021 casualties), the Titanic (1912, 1517 casualties) (Howells,1999), the Lusitania (1915, 1198 casualties) (Frey et al., 2010) and most recently the MV Estonia (1994) (Jasionowski &Vassalos, 2011) (although, the latter was sunk due to a malfunction of the garage door and the survival chances of the passengers were extremely low) and the MV Sewol (2014) (Kim et al., 2016), is to design and implement security and evacuation regulations. Specifically, in the MV Sewol disaster, the high number of casualties (mostly teenagers) was caused due to the inadequate application of the existing security regulations. The last forty years have also been increased in Greece. Especially, from May to September a high number of passengers is ferried to the Greek islands. From 2004 to 2019, over 12 million passengers used passengers' ships or cruisers whistle some of them turning to maritime disasters (SEEN, 2022). One of the main research motivations derives from these marine accidents in Greece. The liner Chrisi Avgi (Panagiotellis, 2017) sunk in 1983, with 28 casualties and after that incident, a series of accidents increased the toll. The sinking of MS Express Samina with 80 human casualties initiated a sequence of disasters. Most notably, the Sea Diamond in 2007) sank with 2 casualties, and the Norman Atlantic in 2014 with 30 casualties (Goulielmos et al., 2009; Gatsou et al., 2005; Samuelides et al., 2009; Giakoumatos & Kalogirou, 2020; T., Quagliati, et al., 2017). Crisis Management for Tourism – A Case Study of The Greek Passenger Shipping Industry. Except for the Chrisi Avgi incident, all other accidents occurred in a calm sea. This element initiates a query for the causes of these high numbers of casualties and if there is a way to reduce them in the future.

Subsequently, the first questions are: "Are there any regulations?" and if any "What are the existing regulations?". After decades of disasters, there are plenty of treaties and organizations that have implemented such regulations, such as the SOLAS (International Convention for the Safety of Life at Sea) and IMO (International Maritime Organization). These regulations and organizations dictate safety standards and rules for all kinds of ships (merchants, leisure, tankers, etc), to improve safety and reduce the probability of maritime disasters. More specifically, SOLAS "describes the requirements for all merchant ships of any flag state to comply with the minimum safety norms" in 13 chapters (Maritime Law, Marinesight, 2020). As for IMO, it is the United Nations agency for the safety and security of shipping. Its purpose is to improve shipping security and avoid environmental disasters due to shipping (IMO, 2020). IMO's regulations are expanded from Marine Safety and Security to Environmental

Issues, Legal Affairs, the Human Element, Administrative Issues, and Communications covering every aspect of the Marine Industry from Ship Building, Travel to Communications, and Human Resources.

The first questions have been answered. Indeed, there are existing regulations implemented by international organizations and treaties. But marines' disasters, leading to evacuations, continue to happen, inflicting casualties. What is the element that is missing? The implementation of these regulations. Subsequently, the next questions are "How do we know that these regulations work and how do we implement them?".

Due to several maritime disasters, passenger ship evacuation on an emergency basis has received increasing attention recently (Stefanidis, Boulougouris, & Vassalos, 2019). Ship designers must run several tests to verify all the amendments and create the concept of a "safe return to port" (Vassalos, Azzi, & Pennycott, 2010). The most common practice to test the safety of a ship is the conduction of Evacuation Drills. Evacuation drills are based on planned evacuation scenarios, with predefined rules and conditions. Several volunteers impersonate the evacuees and some of them are the crew members. When the evacuation starts, the "evacuees' ' navigate through the structure, usually, led by one of the "crew members". Spectators observe the evacuation process, testing the ship's safety and observing the progress of the evacuation. While evacuation drills may provide useful information and data, they are impractical and costly to run (Couasnon, de Magnienville, Wang, & Claramunt, 2019). Moreover, drills, by their nature, cannot include and consider some significant factors such as the psychological pressure due to the stressful and hazardous conditions of an evacuation and the social forces between the evacuees (e.g., parent-child relation, leader-following, herding) (Bryan, 1999). The panic reactions of the evacuees, the unexpected incidents happening during an emergency evacuation, and the changes in the spatial characteristics of a ship's structure, can completely alter the output of an evacuation drill (Vorst, 2010; J.-h. Wang, Yan, Zhi, & Jiang, 2016). On top of that, the drills' high monetary cost, poor repetitiveness (can be conducted only a few times), high risk of accidents, and troublesome legal framework (Ren et al., 2006), make them inadequate tools (Gwynne et al., 2016). Evacuation drills do not take into account, some crucial factors, such as the stressful conditions that affect the human behavior during an evacuation, the crowd's motion under panic (Nygren, 2007), and the motion of a ship, whilst evacuation drills are usually performed in a harbor (as an exception Safeguard project experiments are conducted on ships in the open sea) without the presence of real fires or smoke (although some dummy elements may exist). Focusing on the human reactions and summarizing an evacuation drill does not provoke natural human behavior, when in danger, many "evacuees" idle, and as it has been observed, passengers didn't react, after an alarm call, but only after they were warned by crew members (Proulx & Sime, 1991) and they do not provide sufficient information, especially, if the "evacuees" are unfamiliar with the place. Experimental data, from laboratory experiments, such as fluids, insects, etc., are considered as an abstraction of reality and therefore they lack the ecological validity of the real events, even with the optimum settings (Kinateder et al., 2014).

To this end, this thesis debates solutions to these significant problems, proposing, at first, the implementation of specialized Software Applications of the Evacuation Simulator (ES) genre or a similar genre called Serious Games. As Law and Kelton (Law and Kelton, 2000) state: "a simulator is computer software used to evaluate a model numerically and the gathered data is used in order to estimate the desired true characteristics of the model", while Alvarez notes that "a Serious Game (SG) is a game which its purpose and theme are regulated for application on serious topics and not just for entertainment" (Alvarez & Djaouti, 2011). Simplifying that, ESs and Serious Games attempt to represent the events of a real incident in a computer-controlled environment. In the case of an evacuation, the evacuation structure, the evacuees, the elements, and the event should be set, so that, if the incident is repeated in the real world, it will produce similar events and outcomes. The first attempt for the introduction of Software ES and SG dates to the 70' (Marcus, 1994). Early applications used to be Two-Dimensional, where the evacuees are rendered as dots or crosses over a floor plan. With the advancements in Computer Graphics, the Three-Dimensional ES, such as the VELOS (ES) (Ginis et al., 2010; Ginis et al., 2015) and the EVA - Serious Game (SG) (Ribeiro et al., 2013), are becoming more common, although some specialized simulators are still Two-Dimensional (Gwynne et al., 2000; Chunmiao et al., 2012). We can divide the ES and SG into two types based on the participation or not or real users. Some applications allow human users to control an evacuee and navigate the structure, escaping the danger or performing other tasks (VELOS). Other applications, such as buildingExodus (Gwynne et al, 2001) do not allow the participation of human users and rely only on computer-controlled Bots. These bots are usually enhanced with logic and/or AI and attempt to simulate human behavior or they simply move toward an exit.

However, there have been several Evacuation Simulators and Serious Games, even some specialized-on ships, but many issues still exist regarding their use and reliability. The most important issue, common to evacuation drills and simulators, is the lack or the underestimation of the human factor. A computer-controlled bot can perform human-like activities, but it is not a real human being. Human behavior and psychology cannot be realistically simulated by a bot. Especially, on a ship with so many particularities and all the ADC elements present, a realistic representation of the evacuation is of the utmost importance. Therefore, we know that the Evacuation Simulators can provide valuable results, alleviating some critical shortcomings of Evacuation Drills, but they usually fail to simulate human behavior. We also know human beings have more authentic behavior than bots. How could we successfully combine these two elements and improve the reliability of simulations? Another prominent question is how to effectively apply the existing safety standards and regulations. We have seen that most evacuees are untrained people without any knowledge of the safety rules and standards. The human factor is crucial here and the next question is how we can train these people to react in a more organized manner.

1.3 Research Goals and Research Questions

A solution proposed by this thesis could be the introduction of human beings (players) to serious games for training and testing purposes. A multiplayer serious game/simulator could allow human "evacuees" to participate in an evacuation from their chair. We could also move one step further and allow the simultaneous participation of computer-controlled bots and human players. The next challenge is to motivate the human players to act with realism. Is that possible? What could be the roles of Gamification and Edutainment? What is the Development Environment for such an application? Could Game Engine create Evacuation Simulators/Serious Games? These questions are to be discussed in this thesis and are listed below and discussed in detail in the next chapter:

- How could a Game Engine be a development environment suitable for Serious Games/Simulators?
- How could Behavioral and Movement elements be combined into an Evacuation Serious Game/Simulator?

- What is the impact of introducing human users to computerized Serious Games/Evacuation Simulators?
- What is the impact of the simultaneous participation of human users and computer-controlled bots? Can it increase realism and provide validated results?
- How can we motivate human users to react realistically and use a Serious Game/Simulator as a training tool?
- How could Gamification and Edutainment be applied to the field of Serious Games/Evacuation Simulation towards the training of the evacuees?

1.4 Thesis Outline

This thesis starts by reviewing current evacuation models and then the applications of these models to existing Evacuation simulators. Then, the study dives deeper by reviewing the topics of human psychology and behavior in critical conditions and the most common phenomena during such events. Solutions are also proposed. After assessing the field, the use of Game Engines is proposed for the Development of evacuation simulators. The two previous elements are afterward combined and in the next chapter, the development and implementation of a Ship Evacuation Simulator is tested and assessed, while its outputs are evaluated in the last chapter.

Chapter 1: Introduction

Introduction to the topic of Evacuation and Evacuation Simulators and questions on the importance of valid evacuation practices and measurement.

Chapter 2: Mapping the Topic

This chapter reviews the existing evacuation models and their implementation to Evacuation Simulators. Some important evacuation simulators and models are herein assessed. The research questions are discussed in the chapter.

Chapter 3: Human Behavior in Danger and Evacuation Elements

This chapter reviews human behavior in harsh, potentially dangerous situations, analyzes different behavioral models, and assesses topics that affect the evacuation process, proposing methods to mathematically model them. This chapter discusses the implementation of the previously mentioned elements to evacuation simulators and finally the application of Gamification to ES applications.

Chapter 4: Development Environment

This chapter assesses the Game Engines as the development environments for Evacuation Simulators and sets the rules for the successful development of such software.

Chapter 5: Ship Evacuation Simulator

This chapter details the specification of the Ship Evacuation Simulator (SES), culminating the knowledge of the previous chapters for the development and testing of this software.

Chapter 6: Conclusions

This chapter demonstrates the results after testing the hypothesis of this study on SES.

1.5 Summary

The cruise travel market has met significant growth worldwide. This study proposes a method to improve the safety of marine travel by replacing traditional evacuation drills with virtual ones, adding elements such as Gamification and Edutainment and simultaneous participation of human and computer-controlled evacuees. A virtual simulation allows the safe participation of large numbers of evacuees, has low monetary and computational cost, with high repeatability. Moreover, as this study is conducted during the COVID-19 pandemic, the conduction of evacuation drills is not encouraged for preventing the spread of the virus. The safety of cruise ships can be easily tested even with the participation of real users without the dangers and the cost of a drill. This study discusses the validity of computerized Evacuation Simulators/Serious Game for Ships, with the simultaneous participation of human users and bots, applying the concept of Gamification and Edutainment in a multiplayer environment, towards the training of the passengers of Liners.

PART II - MAPPING THE TOPIC

Chapter 2

2.1 Research Scope and Terminology Definitions

Evacuation Models simulate the movement and behavior of crowds and/or individual evacuees, while they are usually used as the backbone of Evacuation Simulators (Ibrahim et al., 2017) This chapter surveys existing ES and explains some important computerized Simulators' terms. It also presents the evacuation model categorizations in use by most ES, to represent the evacuees' movement and/or behavior. Kuligowski (Kuligowski et al., 2005) and Santos (Santos, G., & Aguirre, 2004), as well as studies on Evacuation models (Lo et al., 2004; Yuan et al., 2007; Shi et al., 2009; Yueming & Deyun, 2008; Krasuski & Krenski, 2019), have proposed several categorizations and the most important for this research, are herein presented, modified to match the needs of this research. The Agents' Movement and Agents' Behavior Models, the User Perspective Model and Visualization and User Participation, are presented below. The next two subchapters present existing ES and analysis on Gamification and Edutainment.

2.2 Defining a Simulator

Ingals (Ingals, 2011) states that "Simulation is the imitation of the operation of a real-world process or system over time". Simulations use one or multiple Models to formulate some system of interest, such as Evacuation (Banks, 2011). Therefore, the age of computers resulted in the development of computerized simulations. Based on Law et al (Law et al., 1991), a Simulator is a computer software used to evaluate a model numerically. The collected numerical data is then used to estimate the desired true characteristics of the model and as a result imitates the operations of real-world facilities or processes. A simulation mimics the Dynamic Behavior of a system and as the complexity of a system increases, the simulator's run and analysis time are increased too (Ingalls, 2011). We also state as a model the assumptions about the function of a system, based on mathematical or logical relationships. To this end, an Evacuation Simulator is a computer program that simulates the process of evacuation incidents and provides us with results similar to the ones, a real-world evacuation incident would have provided. Evacuation Simulators are categorized by their basic features and capabilities and are focused on replicating various aspects of an evacuation incident. A simulator is composed of Events and Models. An Event is an occurrence that changes the state of a system. In a Ship Evacuation Simulator, there could be the outbreak of a fire and the response by the alarm systems and the passengers. A Model is the representation of an actual system and in general should describe the overall problem of a simulation (Banks, 1999). Moreover, a Model summarizes data and predicts observations (Ripley, 2009). A Model consists of the following components: System Entities and Attributes that are the object to be defined, Input (System State) Variables that are the collected data information that defines the function of the simulation and Performance Measures, Resource that provide services to Entities, List Processing, that manage the sequence of the Entities and the Activities and Delays, where Activities is the time to execute an Entity and the Delays is an indefinite duration that is caused by some combination of system condition.

As Maria (Maria, 1997) and (Bradley, 2011) argue that the method to define a Simulation Model a few steps should be followed:

1. Identify the Problem: List the problems and detail requirements.

2. Formulate the Problem: Select the bounds of the problem, set performance issues, formulate the hypothesis, and identify the end-users.
3. Collect and Process Real World Data: Collect data on system specifications, input variables and performance of the existing system. Identify sources of randomness in the system. Select an appropriate input probability distribution for each stochastic input variable and estimate the corresponding parameters.
4. Formulate and Develop a Model: Develop schematics and network diagrams of the system. Translate these conceptual models to simulation software. Verify that the simulation model executes as intended.
5. Validate the Model: Compare the model's performance under known conditions with the performance of the real system. Perform statistical inference tests and get the model examined by system experts.
6. Document Model for future use: Document objectives, assumptions, and input variables in detail.

For implementing a Model, first, the mathematical analysis should be conducted to understand the mathematical model and then to experiment on the model.

Below, the simulator features are categorized, to classify and describe each Evacuation Simulation Software. The selection of the categories is based on the approaches proposed by Klupfel (Klüpfel et al, 2005), Kuligowski (Kuligowski & Peacock, 2005) and Santos and Aguirre (Santos & Aguirre, 2004), on Evacuation Simulators, modified and enriched to match the needs and the purpose of this research. The adopted categories of Spatial Perspective, Agent's Behavior, Agents' Movement, are herein extended with the addition of Scalability regarding the number of agents/bots, User's Participation, Application Areas, Development Software, Development Year, Data Analytics Components and Data Evaluation.

2.3 Defining a Serious Game and Edutainment

Alvares (Alvarez & Djaouti, 2011) states that a Serious Game is a Utilitarian Function(s) plus a Video Game and proposed a categorization based on three criteria: Gameplay (G), Purpose (P) and Sector (S), known as the "G/P/S Model". The Gameplay of a Serious Game combines the Play and the Serious Game and one of the other. The Purpose is based on the aim set by the designer and can be Military Games, Health Games, Puzzles, etc. The Sector is the area of application, such as State & Government, Military, Health, Education, Culture, Science Research, etc. (Johnson, 2007). Mitgutsch (Mitgutsch & Alvarado, 2012) states that Serious Games have six key design elements; Purpose that describes the goals and the intentions of the designers, Content & Information refers to the information, facts, and data offered and used in the game, Game Mechanics which are the "methods invoked by agents for interacting with the game world", Fiction & Narratives that reflects the fictional context of the game, Aesthetics & Graphics refers to the audio and visual language for the visualization and display of the game elements and Framing, which describes the target group, their play literacy and the broader topic of the game. A general rule that separates a classic video game and a Serious Game is that any game built to differ from pure entertainment is a Serious Game (Muratet et al., 2009). The usability of a serious game is based on the compatibility between the learning objectives and the target public (Muratet et al., 2009).

Another approach to Serious Games is the concept of Edutainment, which aims to improve the learning process, introducing some playful elements to serious topics (Miki et al., 2013; Jain, 2011).

Implementing the basic elements of Edutainment, the learners can absorb the knowledge, while they are entertained and its application benefits learners with difficulties in learning (Aksakal, 2015). Moreover, a teacher/trainer can approach the students, taking a role in the game and guide them through the process, while the students are encouraged to improve their social skills by interacting with other learners (Wang et al., 2007). A crucial difference between a Learning and an Edutainment application is that that a traditional Learning application is fundamentally a computer game. A game should not force the user to play, the use is recreational, there are pre-defined, and the game is competitive with specific goals and gameplay rules (Muda & Basiron, 2005).

Based on these assumptions, a Serious Game can provide unique learning opportunities, if it has been properly designed. An Edutainment-based app follows the general rules of Software Engineering (Wang et al., 2007), as shown in the flowchart below (Figure 1).

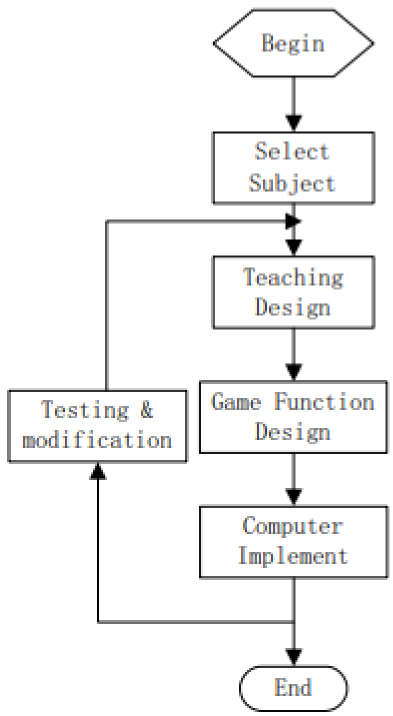


Figure 1. Design Flow of Edutainment (Wang et al., 2007).

A fundamental principle of an Edutainment application should be its ease of use especially, when used by children or adults with little experience with computer games (Wirawan et al., 2013). Based on observations during this research, experienced gamers have generally better performance even when playing Serious Game, thus children and adults with little gaming experience are more suitable as participants.

Serious Games have been used for learning and training purposes in the past, with some examples such as the Kernel Panic, EVA and others. Based on these assumptions that derive from above, the conclusion is that a Serious Game can be used for training while its applications are explained in the next subchapter in detail.

2.4 Shortcomings of Existing Approaches and Research Importance

We have seen that after numerous disasters, evacuations and experiments, several safety standards and regulations have been established. We have also seen that the planned evacuations give us valuable data and contribute to the design of safety and evacuation regulations and standards. The installations, the structures, building and the vehicles are implementing the latest safety standards and the materials are more resistant to fire and produce fewer toxic fumes when burnt. But even with all these measures in place, most of the fatal incidents cannot be prevented as the passengers' crowds are composed of people in distress, of various ages and different backgrounds and thus their behavior is very different than the behavior of the volunteers. In a later chapter, the human behavior in distress and under danger is reviewed in detail, but so far, we can conclude that a dangerous, potentially harmful event such as a fire, a flood, a major crush may send a person to distress and may start ignoring warnings, signs, and regulations attempting to escape. Although the most recent studies have shown that the evacuees seldom act completely irrationally (usually when in hopeless or extremely difficult conditions) a critical event affects human behavior, worsening the conditions of the evacuation.

The focus of this research is the passengers of Passenger Ships and their safety. These passengers are untrained, unaware of their surroundings and their majority are members of families, making liners an ideal ground for the appearance of ADC. Moreover, a high percentage of the passengers are underaged children, elders, and people with disabilities, and as members of families, they tend to move as groups occupying and blocking small areas. Therefore, the Human Factor plays a major role in evacuation, and by improving this element the evacuation's performance can be improved. The main research question is the method as the regulations are in place, but human nature cannot be controlled to follow them.

Subsequently, this work proposes the use of Serious Games while introducing some Simulation elements, applying the theories of Gamification and Edutainment on Evacuation and more specifically on passenger training. This approach alleviates the problem of the big untrained crowd of evacuees. The evacuees could "play" a Serious Game before boarding the ship, gaining substantial benefits. Edutainment and Simulation share many similarities in their goal, but many differences such as their forms of interaction.

2.5 Evacuation Models Based on Agents' Movement

The Movement Models dictate how the model moves the evacuees in the evacuated areas. There are different approaches, and the differences are apparent when the bots are congested to small areas or spaces. These models are applied to computer-controlled bots only.

Proposed Models	Description
Density correlation	The density of the space defines the speed of a single agent or a group of agents.

User’s choice	The speed, flow, and density values are assigned by the user to certain spaces of the building.
Inter-person distance	Each agent is surrounded by a 360° “bubble” defining a certain minimum distance between other agents, obstacles, items, and components of the building.
Potential	A grid cell in space is assigned with a number value (potential). The agents move on the cells while trying to lower their potential. The potential of the cells can be modified by the user, in order to indicate the attractiveness of an exit, the patience of the agent, or the familiarity of the agent with the area.
Conditional	Conditional Behavioral models define the movement of a single agent or a group of agents based on environmental, structural conditions, the correlation, and the interaction with other agents. The model ignores much of the effect of congestion areas.
Acquiring knowledge	Acquiring Knowledge models focus on the knowledge, where it is acquired during the evacuation. The knowledge consists of the recognition of congestion, bottlenecks, etc. There is no real movement algorithm because evacuation time is not calculated.
Unimpeded flow	Unimpeded flow models calculate the unimpeded movement of the agents while adding or subtract delays and improvement times to deduce the final evacuation time result.
Cellular automata	The agents of this model move from a cell on a grid space to another cell by the simulated throw of a weighted die.

Table 1 Agent’s Movement (Kuligowski et al., 2005)

2.6 Evacuation Models Based on Agents’ Behavior

The evacuee’s Behavior Models represent the overall behavior of the bots during an evacuation simulation. The table retrieved from Kuligowski (Kuligowski et al, 2005) lists the different models:

Proposed Models	**Description**

No Behavior	The agents can move but no behavior is implemented on them.
Implicit behavior	Represents those models that attempt to model behavior implicitly by assigning certain response delays or occupant characteristics that affect movement throughout the evacuation.
Probabilistic	Many Rule-based models are stochastic, and the results are calculated by the continuous repetition of certain simulation sessions, which produce various outputs.
Rule-based	Rule-based Behavior is implemented by (i) enhancing the agents with personal characteristics that affect their reaction and movement, (ii) introducing incidents, environmental conditions, and (iii) allowing the correlation and interaction between the agents. When a condition is triggered, the agent reacts accordingly.
Artificial Intelligence	Artificial Intelligence models attempt to simulate the behavior of the agents based on Artificial Intelligence equations.

Table 2. Agents' Behavior (Kuligowski et al., 2005)

2.7 Evacuation Models Based on User Perspective

Regarding the User Perspective in evacuation simulators, our most common perspectives are the Two-Dimensional and the Three-Dimensional. On Two-Dimensional simulators, the bots are represented as dots, arrows, circles, or other simple symbols. The Movement and the Behavior can be implemented but the Visualization of the area is not possible or is extremely limited. As an example, in the case of a Bottleneck, we cannot see the actual area but just symbols congested to a narrow corridor. Moreover, the introduction of human players as evacuees is not possible. The Three-Dimensional simulators, on the other hand, offer improved Visualization and additional features, such as the listing of a ship, can be implemented, but they are usually more expensive computationally and their development is more complicated. Therefore, the two categories are listed below:

Proposed Models	Description
Two-Dimensional	These models represent the evacuated area and the evacuees as symbols on a floor plan.

Three-Dimensional	These models represent the evacuated area and the evacuees as Three-Dimensional entities.

Table 3. User Perspective

2.8 Evacuation Models Based on User Participation Mode

The last categorization is based on the introduction of users, at what degree. Some Evacuation Simulators are exclusively operated with computer-controlled bots. An administrator sets up the evacuation area, rules, and values, and then the evacuation is performed by the computer. On the other hand, there are Evacuation Simulators that allow the participation of human users. The combination of these two categories is one of the debates introduced with this thesis.

Proposed Models	**Description**
Bots-only	These models allow only the participation of computer-controller bots in ES.
Human Users	These models allow the introduction of human users in the roles of the evacuees.
Hybrid	These models combine computer-controlled Bots and Human users.

Table 4. User Participation Mode

2.9 Data Validation

It is, strongly, recommended to compare the results of computer simulations with information collected from real accidents or experimental data. Another approach is the collection of data from evacuation drills. Lastly, data from previously conducted computerized evacuation simulators that have been validated could be also considered. This feature describes the methods used by the developers or the users of each of the Simulation Software to evaluate the credibility of the results of Evacuation Simulators, which are provided by the evacuation simulations. Data for evacuation factors can be collected from other studies on the topic.

The main sources of previously sample collected data are:

- Real evacuations (such as the sinking of a ship or a forest fire).
- Evacuation Drills.
- Previous computerized simulations (from the same or another simulator, that has been validated).
- Experimental Data (psychological, behavioral, fire or smoke spreading, material properties, fluid, and insect movement experiments, etc).

2.10 Related Work/Existing Evacuation Simulators

Users' Immersion is one of the key features of virtual environments, such as computer games or simulators. Brown and Cairns (Brown & Cairns, 2004, April) argue that in the stage of the "total immersion" the user's senses are cut off from the real world and only the end of the computer game is all that matters. The level of immersion is defined by i. the interest that a virtual world causes to the player, ii. the permanent existence of new tasks to complete, iii. the continuous update of the challenges and iv. the feeling of flow, where people are completely absorbed in the activity (IJsselsteijn et al., June). The known limitations of simulators include the lack of physical conduct with the phenomenon and effects such as motion sickness (Menin et al., 2018). The evacuation simulators presented in this subchapter, establish the foundation of this work (detailed tables displaying all the reviewed simulators can be found in Appendix A - Table 5).

2.10.1 ACSIT - DPM VR System

Ren (Ren et al., 2006) proposed, in his study, the application of computer simulation and information technology for disaster prevention and mitigation. The proposed simulator is purposed to simulate fire emergency evacuation drills while providing emergency evacuation training. The main concept is that a single player controls a virtual avatar while performing firefighting tasks. The simulator was developed combining the Vega Engine for the development of the virtual environment, the Multigen Creator for the rendering of the 3D building models, and the Fire Dynamics Simulator (FDS) for the simulation of the fire sources, while the algorithms are written in Visual C++ 6.0.

Feature	Description
Agent Movement	Conditional
Agent Behavior	Artificial Intelligence
Scalability/number of bots	Not specified
Areas of Application	The area design with Multigen can be very large and the areas can be of any kind. Big cities, farms, vast areas, and structures can be designed and represented
User Participation	● User controls an agent that performs fire-fighting tasks and participates in the evacuation. ● The Head Mounted Display can be mounted to improve immersion.

Perspective	Three-dimensional
Development Software	Vega (Virtual environment creation) Multigen Creator (3D building models) Fire Dynamics Simulator (Fire's behavior) Visual C++ 6.0
Development Year	2006
Data Validation	● Recording and replaying features. ● Calculation and prediction of evacuation routes as a numerical simulation, which consists of the creation of paths in the virtual environment based on the simulation results, the creation of a virtual human model with Multigen Creator, and the travel of a human model along the designated path.

Table 5. ACSIT - DPM VR System Features

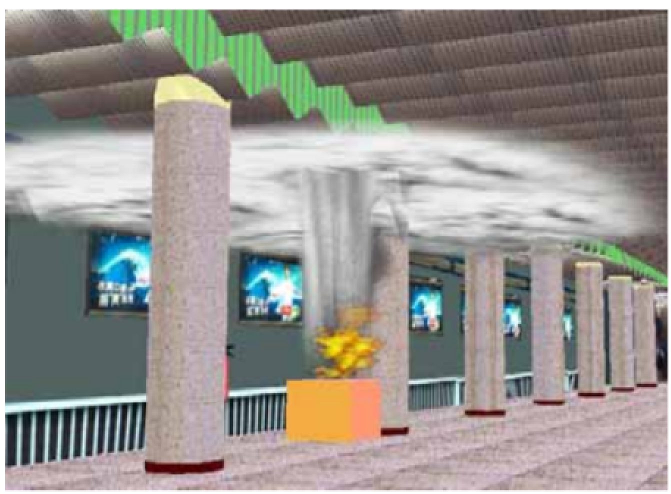


Figure 2. Screenshot from ASCIT-DPM VR System (Ren et al., 2006)

2.10.2 VELOS

Ginis et al. (Ginnis et al., 2010; Kostas et al., 2011; Kostas et al., 2014) developed the VELOS Simulator, a multi-user Virtual Reality (VR) system that aims to support designers on the assessment of the activities and movement of the passengers and the crew members of a ship, early in the design process, for normal and hectic conditions of operations, to improve the design of passenger ship (Ping et al., 2018). The VELOS assesses various ship features, such as the evacuation process, ergonomics, and comfortability. This work is in line with IMO Interim Guidelines for Evacuation Analysis of Passenger Ships and aims to develop an integrated environment for the rational analysis and assessment of real emergency conditions, removing restrictive assumptions and omissions of IMO, which lead to the need for safety factors. Although VELOS is not proposed only for evacuation simulation, as it aims to assist ship designers, it proposes some interesting features, such as the 3D environment and the ship's movement.

Feature	**Description**
Agent Movement	Conditional
Agent Behavior	Artificial Intelligence
Scalability/number of bots	max. 10.000
Areas of Application	Passenger Ships
User Participation	Yes
Perspective	Three-dimensional
Development Software	VRSystem
Development Year	2009
Data Validation	Three test cases are presented: the first one performs evacuation analysis for a typical scenario in intact condition, using both the simplified and VELOS advanced method; the second one deals with the evacuation analysis in damaged conditions using VELOS advanced method, while the third one exploits the simplified method in order to propose design improvements for the RO-RO (Roll on - Roll off) passenger ship.

Table 6. Velos features

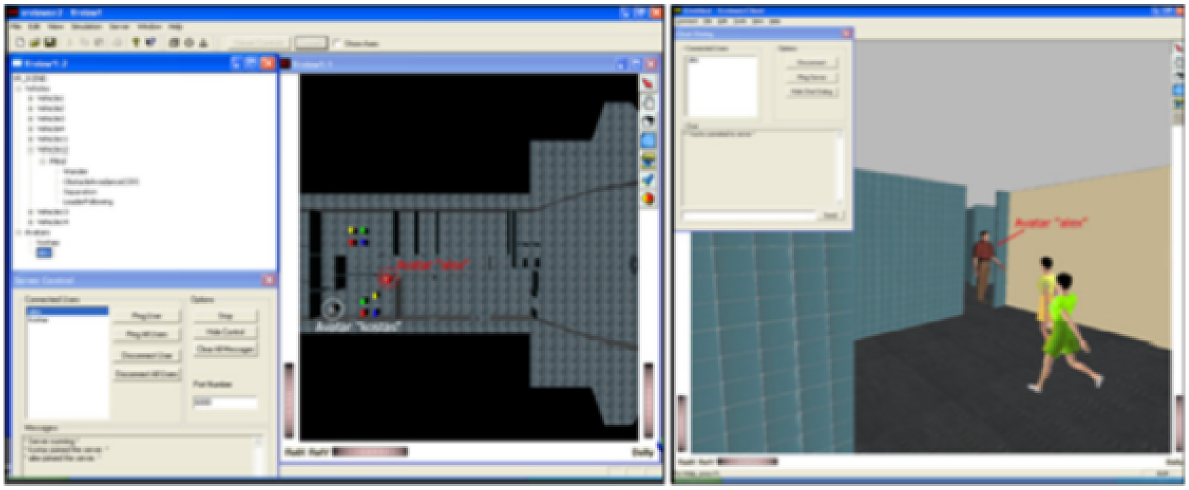


Figure 3. Screenshot from VELOS (Ginnis et al., 2010)

2.10.3 EVA (Serious Game)

Serious Game - EVA (Ribeiro et al., 2013; Silva et al., 2013) is a 3D game-based evacuation simulator and therefore combines a Simulator and a Serious Game. Serious Game simulates the evacuation of buildings by a crowd of computer-controlled bots with the participation of only one human player (the developers claim that the next step is the participation of more human players). Furthermore, this application assesses the overall use of Game Engines for the development of evacuation simulators. Ribeiro et al. Game (Ribeiro et al., 2013) state that the Serious Game extends a popular game engine to implement a pedestrian simulator to study evacuation dynamics and to provide an appropriate environment for testing the influence behavior of egresses of a building in hazardous situations, such as fires. EVA is proposed for use in multiple environments, such as a hospital, and thus includes the addition of evacuees on wheelchairs (a common view in e.g., hospitals). After the end of an evacuation session, the players are presented with a questionnaire about their background, training, etc (Silva et al., 2013; Silva et al., 2013, May).

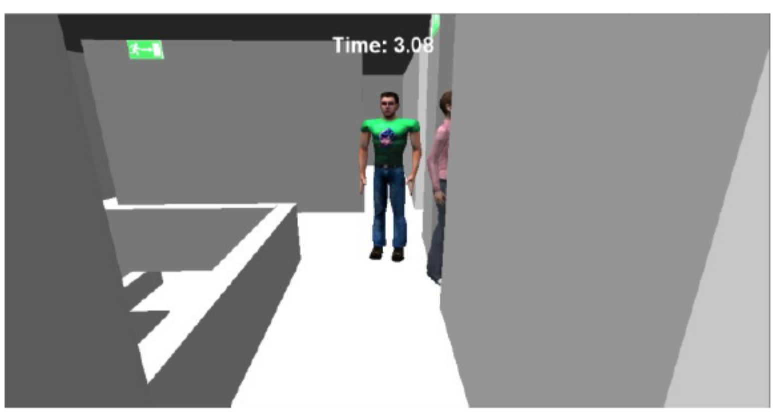


Figure 4. Screenshot from Serious Game - EVA (Ribeiro et al., 2013)

Feature	Description
Agent Movement	N/A
Agent Behavior	Rule-Based
Scalability/number of bots	max. 10.000
Areas of Application	Multistory Buildings
User Participation	Yes
Perspective	Three-dimensional
Development Software	Unity Game Engine
Development Year	2012
DataValidation	After a short test of the game's control system, real players participated in single-game evacuation fire drills. Computer-controlled bots participated simultaneously. The developers were interested in: ● The overall evacuation time (found higher than the real needed time) ● The behavior and movement of a human during an egress The capabilities of a Game Engine as a developing environment for a Serious Game.

Table 7. Serious Game - EVA features

2.10.4 Cell - DEVS

Cell - DEVS is based on the DEVS model, which consists of the atomic and the coupled model. The Atomic model is described in Figure 4. Cell-DEVS is a paradigm and various specifications have been developed such as the CD++ (Wainer & Giambiasi, 2001). As stated by Ha (Ha et al., 2012) “the basic model has specifications for the dynamics of the model. The coupled model, on the other hand, provides the method of assembly for several atomic and/or coupled models to build a complex system hierarchy”. The cell spaces in Cell–DEVS are considered discrete event models. Each cell is seen as a DEVS atomic model that can be updated at each time step ((Ha et al., 2012). The data validation of Cell-DEVS is based on tests proposed by IMO (Roh & Ha, 2013).

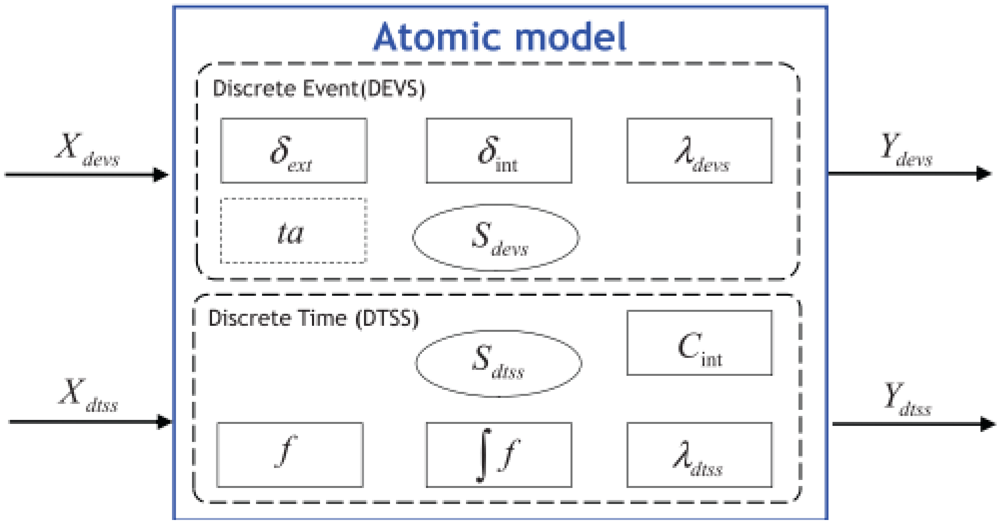


Figure 5. DEVS Atomic Model (Ha et al., 2012)

Feature	Description
Agent Movement	Cellular Automata
Agent Behavior	Implicit Behavior
Scalability/number of bots	At least 1892
Areas of Application	Multiple areas and disciplines (herein reviewed the human behavior in ship evacuation)
User Participation	No
Perspective	Two-Dimensional
Development Software	N/A
Development Year	2009
Data Validation	To validate this model, the 11 tests noted in the IMO MSC circ.1238 Annex 3 guidance on validation/verification were implemented. The test verified through elementary scenarios that the

	basic subcomponents work according to the IMO tests.

Table 8. Cell-DEVS features

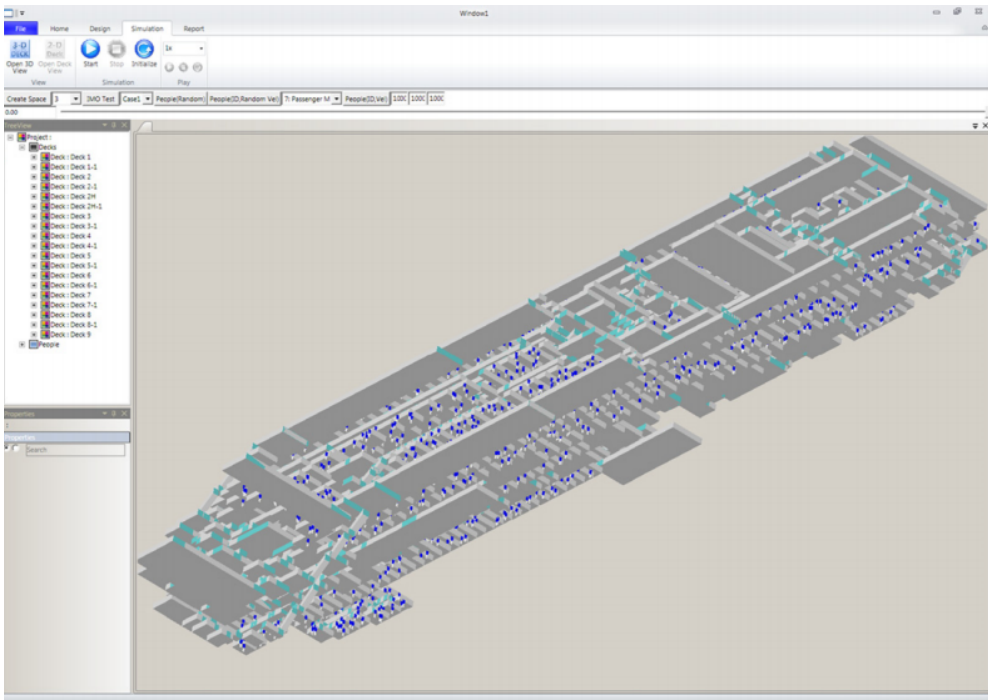


Figure 6. RO-RO Passenger Ship View (Ha et al., 2012)

2.10.5 EPES

Earthquake Pedestrian Evacuation Simulator (EPES) is an evacuation simulator specialized for after Earthquake evacuation of areas and buildings (Quagliarini et al., 2014). It involves Social Forces and Potential movement. Evacuees spawned in the same building are also assigned with a cohesion factor under a cohesion matrix as an input variable (Figure XXXXX), as well as families. The validation is a combination of experiments in a real environment (a part of the historical urban city centre of Corinaldo in Italy), analysis of videotapes and data from past earthquakes (Bernardini et al., 2016; Bernardini, 2015).

Feature	**Description**
Agent Movement	Potential (elements of Social Forces)
Agent Behavior	Rule-based
Scalability/number of bots	N/A
Areas of Application	Different areas subject to earthquakes

User Participation	No
Perspective	Two-Dimensional
Development Software	• IDE-Eclipse • Alan tool plugin • Java
Development Year	2014
Data Validation	• This model validates the results of drills conducted by the research team. • Videotapes analyzed for analyzing evacuees behavior. • Analyzing past earthquake results.

Table 9. EPES features

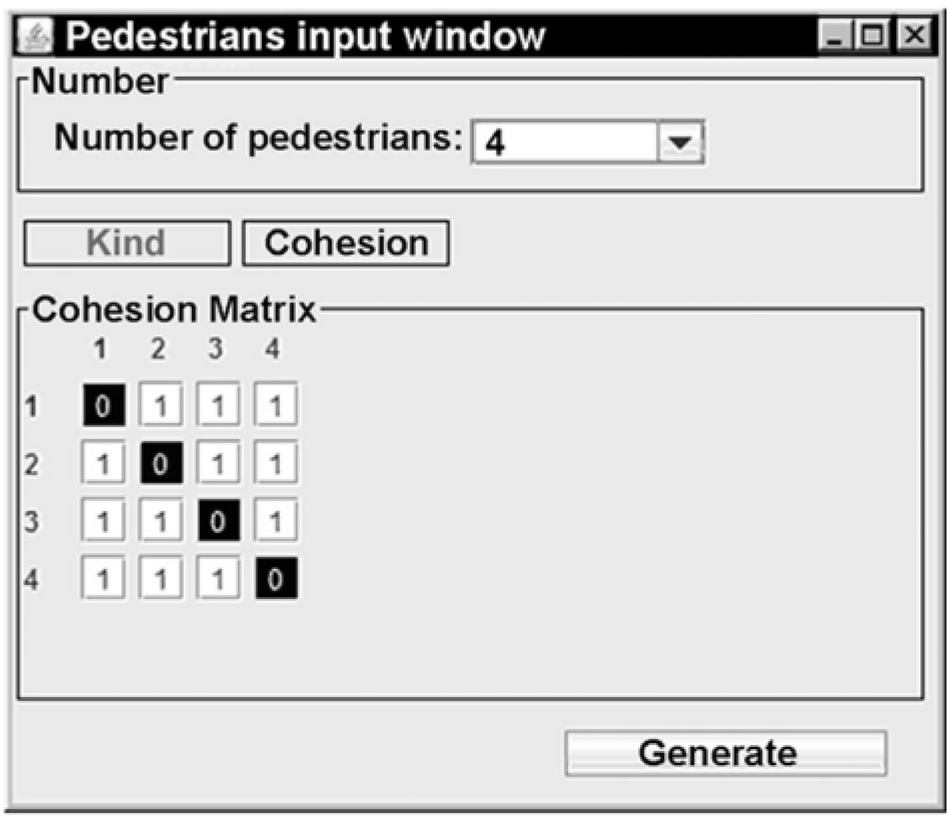


Figure 7. EPES input Cohesion Matrix (Quagliarini et al., 2014).

2.11 Related Work/Existing Serious Games

After reviewing a few Simulators and Serious games, we need to go over some existing Edutainment-based applications. An Edutainment application should not aim to entertain the user, but its context should provide some training and knowledge. For reviewing the features of Edutainment applications, the matching elements of the Simulators.will be used.

2.11.1 MediaEvo Project

MediaEvo Project is a didactic game for learning about the Medieval world, reconstructing the everyday lives of the residents of the town of Otranto (Italy). Specifically, the age is during the Frederick Age (13th century) depicting the everyday life of the commoners and the authentic video of a medieval city (De Paolis, 2011). The application attempts to communicate the cultural heritage and broadcast the history of the area. The designers have included tasks and challenges such as the Virtual Treasure Hunt, where the players are searching for a treasure while navigating among different locations. The development environment was the Torque Game Engine with ESRI ArcGIS for terrain design, making it a good example of a Serious Game Development with Game Engines. MediaEvo also includes an Augmented Reality component, developed with the ARToolkit, where the users can explore and play while navigating modern locations (De Paolis et al., 2011). The application works in a 3D virtual environment, with intelligent agents, that simulate the behavior and habits of the medieval townsfolk, while the building and the other constructs are copies of real medieval buildings. The buildings were designed using CAD. The users have targets and goals to achieve, and the game progress is dependent on their action, improving the immersion and the interactivity of the application (De Paolis, 2009). MediaEvo is described as an example of a Serious Game, in a multiplayer three-dimensional perspective that implements the principles of Edutainment.

Figure 8. MediaEVO Project Game Session (DePaolis et al., 2011).

Feature	Description
Agent Movement	-
Agent Behavior	Rule-based
Scalability/number of bots	N/A
Areas of Application	Medieval Otranto
User Participation	Yes
Perspective	Three-Dimensional
Development Software	● Torque Game Engine ● ESRI ArcGIS ● ARToolking (AR Edition)
Development Year	2009
Data Validation	● Not a Simulator.

Table 10. MediaEvo Project Features (DePaolis et al., 2011).

2.11.2 C-VISions

Irawati (Irawati, 2008) describes the C-VISions as “a collaborative learning environment that provides experientially grounded learning where students can experience physics-related phenomena and discuss the causes underlying the experienced phenomena with collaborating peers”. It provides the tools for the development of smaller games such as the Domino Effect Simulator towards the teaching of Physics, through the parameterization of the input and the evaluation of the output and the Social Word for various learning groups' communication and exchange of information (San Chee et al., 2002). C-VISions supports a VR and an AR edition, enhancing the experience further.

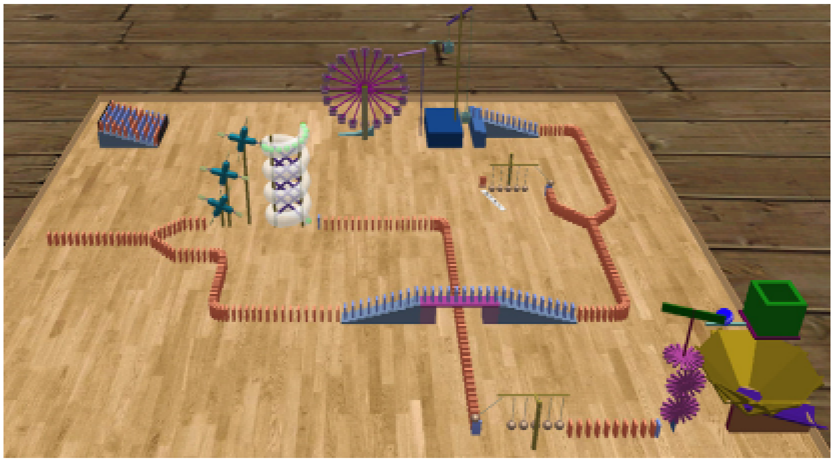


Figure 9. C-VISion - Domino Effect Simulator Gameplay (Irawati, 2008)

Feature	Description
Agent Movement	-
Agent Behavior	Varies
Scalability/number of bots	N/A
Areas of Application	Varies
User Participation	Yes
Perspective	Three-Dimensional/Two-Dimensional
Development Software	• VARU Framework • OpenSceneGraph • OSGART Library • ARToolkit (AR Component)
Development Year	2002
Data Validation	• Experimental Data.

Table 11. C-VISions Features (Irawati, 2008)

2.12 Research Importance and Questions

After reviewing and analyzing the function and the results of the above-mentioned Evacuation Simulators, Serious Games and the principles of Gamification and Edutainment, some conclusions have been reached and they comprise the basic idea and consideration for the writing of this work. The current research is attributed to designers of Serious Game and Simulator, who develop Three-Dimensional SG and Simulators, using Game Engines. Taking into consideration these assumptions, this work will propose solutions to the research questions that originate from these conclusions.

The primary question to review is the suitability of Game Engines as development environments. So far, we have seen that many of the example applications reviewed here used Game Engines for their development. Therefore, we have a solid precedence indicating that this is possible. The novel approach will be the combination of a simulated ship environment, with computer-controlled bots and human players for training of these players in emergency situations. The basic idea behind this is to substitute the boring and complicated safety instructions, that are in general ignored by the passengers, with a recreational activity that achieves the same goal. Most evacuation egress focuses on the technical aspect of the evacuation ignoring or underestimating the importance of the passengers (Nevalainen, 2015). The present research focuses on the passengers and their perspective, attempting to create a valid and fidel virtual environment and allow the users to actively participate. The questions that this research will attempt to answer are i. if the existing Game Engines are suitable for Serious Game/Simulators development, ii. if the development is feasible, iii. how computationally expensive this approach is.

The next question is if the ESs and Serious Games have different scopes and purposes. Simulators and Serious Games such as the EVA (Ribeiro et al., 2013) and ACSIT - DPM VR System (Ren et al., 2006) purposed to evaluate and improve safety measures, whilst simulators such as VELOS are primarily focused on the ergonomic design of ships, before the building phase (Kostas et al., 2011). On the other hand, MedEVO Project teaches history (DePaolis et al., 2011). Therefore, the evacuation simulators/serious games ought to be assessed according to their scope. As for the ES, a categorization could be *Safety Evacuation Simulators (SaES)* and *Structural Evacuation Simulators (StES)*. Safety Evacuation Simulators focus mostly on Evacuation Modelling, Human Psychology and Crowd Movement aiming to primarily provide results related to the evacuation process and the human movement. Structural Evacuation Simulators evaluate the spatial elements of an evacuation, such as the structure, the signs and consider the human element from the spatial perspective. Their purpose is the improved security of structures, buildings and vehicles, by assessing the impact of spatial elements. The Serious Game comprises a unique type and their purpose is to train and educate without the burden of traditional teaching. These three different approaches create a gap, as they aim to evaluate different things, but they end up missing some critical elements of the other category. As an example, a StES may realistically simulate the impact of a narrow corridor during an evacuation, but it may lack the Behavior of the crowd of the evacuees, under stressful conditions. Therefore, a new approach is proposed that combines elements from all the above-mentioned categories, towards the realistic simulation and training in virtual sessions. Spatial, Safety, and Didactic elements should be combined to provide a holistic outcome. The evacuees should not be just automata that are moving under specific rules, but intelligent agents, capable of interacting with the environment and/or other evacuees. The valid question could be “Might we combine these three approaches?”.

So far, we are not implementing a novel approach, and this is where the second question comes. This approach has been implemented to old 2D simulators such as PedGo (partially), a stochastic, multi agent model, in which the evacuated area is represented as quadratic cells and the evacuees occupy them (Klüpfel, & Meyer-König, 2005; Klüpfel & Meyer-König, 2014), while moving or the FDS+EVAC, which represents the evacuees as elliptical shapes that resemble the area occupied by the human body (Korhonen et al., 2010). The missing part of these 2D simulators is that they are unable to include real users as evacuees. Some of the 3D simulators (VELOS, ACSIT - DPM VR System) allow the introduction of human players, which wouldn't be possible in a 2D environment, or it would not be realistic. A dot or an artifact should not be considered to resemble an evacuee, when controlled by a human player, as they lack human perspective and spatial cognition. In 2D simulators. The evacuees are enhanced with behavior or even Artificial Intelligence, but they lack the impact of the behavior of real users. The purpose of the ES is to increase the repetitiveness of simulations (which can be achieved) and to reduce the danger to human lives during egresses. The question is how much can humans be removed from a process, which is closely associated with humans? An evacuation is an anthropocentric phenomenon and therefore the behavioral and spatial impact of real humans ought to be assessed, directly and indirectly, involving them in the process. Subsequently, the third question is: “Should we allow human players to be involved as evacuees?”.

Existing evacuation simulators/serious games focus on the representation of the dynamics and the course of evacuation egresses. Even the applications that take into consideration the human factor, their nature is to assess topics such as the spatial, behavioral, and structural phenomena. The main query here is the human element and how this element affects the outcome of an evacuation. The ADC is instigated by the lack of warnings, announcements, signs, desperate conditions, and very severe accidents but one of the crucial elements of these conditions is human nature. The planned evacuations are costly, lengthy, and dangerous and it would be impossible to be conducted for all the passengers of a ship or an airplane, as this may disrupt the travel schedules. In this work, it will be shown that the ADC usually appear when the crowd of the evacuees is untrained and unaware of their surroundings and the proposed solution for this major issue is the training of the evacuees by a 3D computerized Serious Game with elements of Simulation that uses Gamification and Edutainment principles to keep the interest and immersion of the users.

The next question is related to the human players. The evacuees in a real accident are in immediate danger for their life. Therefore, their behavior is not that of a user, playing a computer game, even if this game is in fact a simulator. Controlling a virtual evacuee, a player experiences what is called Player Experience, which culminates in the User Immersion. This transition has four stages: Entertainment, Educational, Aesthetic and Escapist. The Escapist stage leads to User Immersion (UIm) (Ermi & Mäyrä, 2005). UIm is a stage where the player is disconnected from the real world and their behavior matches the flow in the virtual environment. Some computerized evacuation simulators allow the real-time participation of human players, mostly in single-player mode. This element is considered of high importance as one of the goals of the application is to keep the users immersed, through a sequence of challenges and goals. Therefore, this element is not completely new, but it is useful to question if the participation of real human players may contribute to the realism of an Evacuation Simulator. The third question is: “Could the participation of human players increase the realism?”.

This guides us to the next question. So far, we have seen that the simulators allow either the participation of users in 3D environments or the participation of only computer-controlled evacuees (bots) in 2D environments. We also know that Behavioral (to bots) and Spatial elements (to structures) can be introduced to 2D as well as to 3D ES. Finally, we assume that the participation of a human player, under specific circumstances can match or close the behavior of a real evacuee, if the player is totally immersed. The fourth question is “Could we improve the realism of an evacuation if Human-Controlled Evacuees and Computer-Controlled Evacuees simultaneously participate in Evacuation Sessions and how Gamification can contribute towards this goal?”. This question is important, although we focus on the training of the evacuees, the realistic behavior of the computer-controlled bots and the overall evacuation should contribute to the user immersion.

To Summarize, the main research question of this work is if the simultaneous participation of Human-controlled evacuees and Computer-controlled evacuees, in a 3D environment, with the application of the principles of Gamification, in Evacuation Simulators, could be applied to a Serious Game with Elements of Simulation, towards the training of the evacuees in harsh conditions before they even board a ship. Moreover, the Game Engines are tested and assessed for their suitability as development frameworks of Evacuation Serious Game/Simulators. For this work, the framework of the simulation should be the Passenger Ships, as they comprise most of the spatial and behavior elements present in most evacuations (congestions, bottlenecks, counterflow, etc.). With the proposed approach the problems of i. the insufficient training and the lack of familiarization with the structure, ii. the danger evacuation drill tests and their limited repeatability, iii. the lack of human participation in 2D Evacuation Serious Game and Simulators, iv. the participation of only computer-controlled bots or only human-controlled evacuees of most 3D simulators, and v. the absolute absence of any immersion and motivation of the human players, are alleviated, while the Game Engines potent as development frameworks for Evacuation Serious Games and Simulators is assessed.

2.13 Summary

Existing work on Evacuation Models has provided us with models that describe the evacuation process. These models are used to assess different aspects of evacuation and most of them have been implemented in existing Evacuation Simulators. The basic categorization of these models is between the ones that aspire to describe an evacuation primarily as a Spatial phenomenon and the ones that describe it primarily as a Behavioral phenomenon. The evacuation simulators mentioned above in this chapter are the foundation of this research. Although this research is focused on Three - Dimensional Evacuation Simulators, the foundation of Two - Dimensional Simulators are also studied. In the Chapter, we learned about Simulators and Serious Games, the simulation models, Gamification and Edutainment, and events and their implementation to Evacuation, after reviewing existing applications. The reviewed applications are ACSIT - DPM VR System, VELOS, Serious Game - EVA, Cell-DEVS, EPES, MediaEvo, and C-VISions based on their Agent Movement and Behavior model, their Scalability, Areas of Application, User Participation, Perspective, Development Environment and Year and Data Validation (adjusted to match each application). In the next chapter, Human Behavior and the Evacuation Factors will be reviewed.

Chapter 3

3.1 Human Behavior and Evacuation Factors

The main point of this thesis is the Human Behavior in Critical Conditions (HBCC) and the familiarization and training of the participants with the structure and the idea of urgent evacuation. To extract reliable conclusions, validate the results of this research and implement elements in an ES, the HBCC had to be analyzed and assessed. Some of the most important questions are:

- How unpredictable is human behavior in critical conditions?
- How reliable is the literature?
- What factors affect human behavior and movement in dangerous conditions?

This chapter is attributed to this aspect of the research, attempting to study the human behavior and the evacuation factors, to assess their implementation on Evacuation Simulators. This assessment attempts the first and the third question set in Chapter 2, reviewing the implementation of human behavior under a given evacuation environment. This chapter discusses the impact of the Behavioral Models, Human behavior, and the Evacuation Elements (EE), such as Fire, Smoke, etc., in real incidents, aspiring to review their correlation and mutual impact.

3.2 Introduction

A disaster may occur before, during, or after any type of event or circumstance that causes people to congregate (Dickie, 1995). An established problem is a noted difference between the real incidents and evacuation drills. When the passenger liner Saint-Malo was stranded off the shore of France and listed, the total evacuation time was 1 hour and 17 minutes. The time of more than nine evacuation drills based on this incident was 8 minutes (ten times less). Although it coexists with the listing and motion of the ship, the human psychology factor is one of the variables that explain this gap (Lee et al., 2004). Another aspect of the problem is that the evacuation plans (i) lack flexibility as they do not include dynamic information such as a collapsed wall that blocks an exit, (ii) lack intelligence as could guide people to jam at exit routes, (iii) cannot provide sufficient information, especially, to people unfamiliar with the place (Pu & Zlatanova, 2005). The situation worsens in case of the absence of even these plans and measures. The unpredictable nature of the human behavior combined with structural and security methods inadequacy, might increase the evacuees' stress and provoke reactions that vary from total retirement and anxiety to uncontrollable panic reactions.

Moreover, the information and the degree of its comprehension by the evacuees is another challenge. Evacuation drills on uninformed passengers about the conduct of the drill show that they didn't react after an alarm calling but only after they were warned by crew members (Proulx & Sime, 1991), significantly impacting the progress of the evacuation. A question that could be asked is how we can acquire credible output from evacuation incidents. Zhao et al (Zhao et al., 2009) propose as sources of human behavior: (i) the evacuation drills, (ii) the simulations, (iii) the post-real incidents surveys, and (iv) the laboratory investigations. However, they also state that the only reliable sources for the retrieval of results on human behavior are the post-real incidents surveys.

3.3 Human Behavior in Harsh Conditions

Human behavior is categorized in psychological behavioral models based on certain sets of reactions. Instead of the recognition of panic as a dominant reaction during very harsh conditions (fires, earthquakes, floods, etc), Quarantelli states that panic is a statistically infrequent behavior and sets five characteristics present on noted panic behavior: i. Previously formed impression of the existing situation, ii. no close relationship among the people in danger, iii. fear of the subject of being trapped, iv. sense of powerlessness and v. feeling of sole isolation (Quarantelli,1975). There is a common belief based on movies and narrations, which is also found in older studies on human behavior. This belief dictates that during emergencies humans become animals and act completely irrationally. By the 50' this opinion was revised and panic behavior was characterized as asocial collective behavior. The narration changes and people are considered to take care of their own needs but not the needs of others. This view was replaced in the 80s when studies showed that people either behave like "animals" or abolish their social ties. In contrast, it is most recent studies that argue that these bonds become stronger during emergencies (Santos & Aguirre, 2004). Irrational behavior has been noticed when the source of the danger and the information about it is ambiguous or inadequate; especially occupants familiar with a structure most likely use fire-escape routes, then unfamiliar ones (Ramachandran, 1990). Therefore, if the occupants are familiar with a place, possibly briefed about the lurking danger, aware of the danger, and well-informed have a very low probability to panic and act irrationally, so is there a specific instigator of panic? According to Mehran (Mehran et al., 2009; Zanlungo et al., 2011), there are three main approaches in modeling human behavior in dangerous conditions i. the Macroscopic models approach which determines the pedestrian's motivation in movement and treats crowd behaviors because of a self-organization process, ii. Macroscopic models focus mainly on goal-oriented crowds, that are divided into smaller groups, and then their behavior is motivated instead of their movement, iii. Hybrid models combine elements of both.

As noted above, the increased stress levels may lead to panic under certain circumstances. A sequence of ambiguous information results in highly induced stress levels. A stress model depicts the increment of stress levels in five stages, starting from low stress and culminating in high-stress levels. The alteration of the subject's emotional state ranges from Control to Uncertainty, Fear, Worry, and finally to Confusion. Based on real incidents, the conclusion that has been reached is that informing the public is a factor of reduced stress (Proulx, 1993) and therefore an announcing system is of crucial importance, especially, is usually busy areas such as train platforms, ships, or hotels.

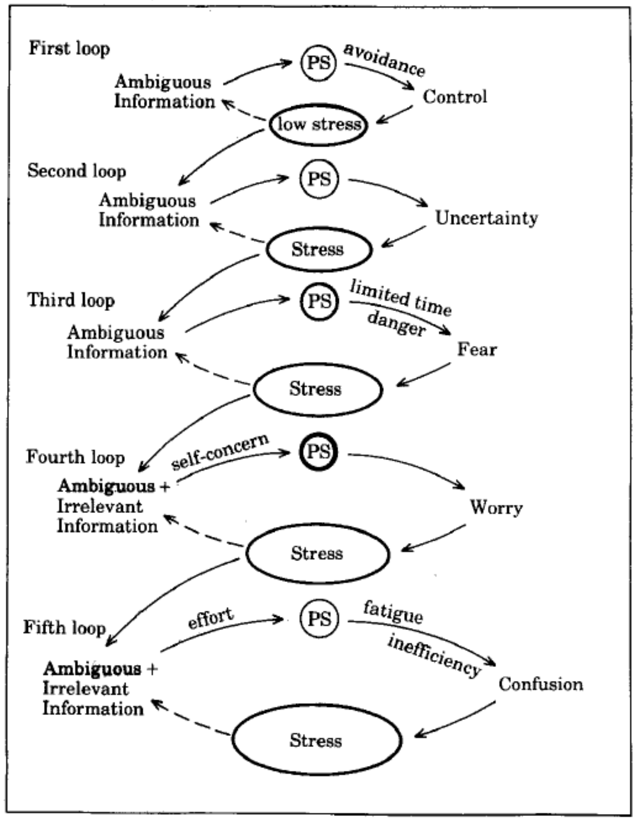


Figure 10. Stress model as proposed by Proulx (Proulx, 1993).

Three Behavioral models are presented below, ordered from the oldest to most newly established; The Panic Model, the Affiliation Model, and the Protective Action Decision Model, described below.

3.3.1 Panic Model

The first reaction of a panicked person is to rush away from the source of danger. The Panic Model implements the idea that people leave a building in groups and the fatalities are due to the inability of evacuees to use the existing escape facilities. An entrapment leads the subjects to panic. Under this condition, the panic model assumes that the cohesion of groups, even families, is dissolved and their members do not act jointly and try to rush toward an exit. Experiments have shown that a competitive behavior surfaces i. when the threat level is high, many evacuees (even strangers) follow a route and the subject follows them, and ii. when there are difficulties in communication with other evacuees (Sime, 1983).

Weinberg mentions that Leadership training and experience may be important factors in panic prevention. Gear identification of a leader may prevent the low positional power condition characteristic of panic situations (Weinberg, 1978). These factors indicate that panic situations are mostly characterized by poor leadership.

In contrast to the common belief, the panicked evacuees act rationally if they have knowledge of the nature of the hazard. The preliminary hypothesis under consideration predicts that panic is associated with high task structure, low interpersonal relations, and low positional power. It is also noted that subjects inside unfamiliar places tend to panic more frequently than in familiar places (Wang et al., 2016). To model the Panic Model, we use the Social Force model by Helbing (Helbing et al., 2005; Li et al., 2014). Helbing states that human behavior is not unpredictable, with the exception of very complex situations. The social forces or social fields model is displayed in Figure 10 below and based on it, Helbing concludes that a behavioral reaction is dependent on the stimulus and the personal goals of a person and then a set of behavioral alternatives is chosen, towards the objective utility maximization. The Social Forces model works better in goal-oriented crowds.

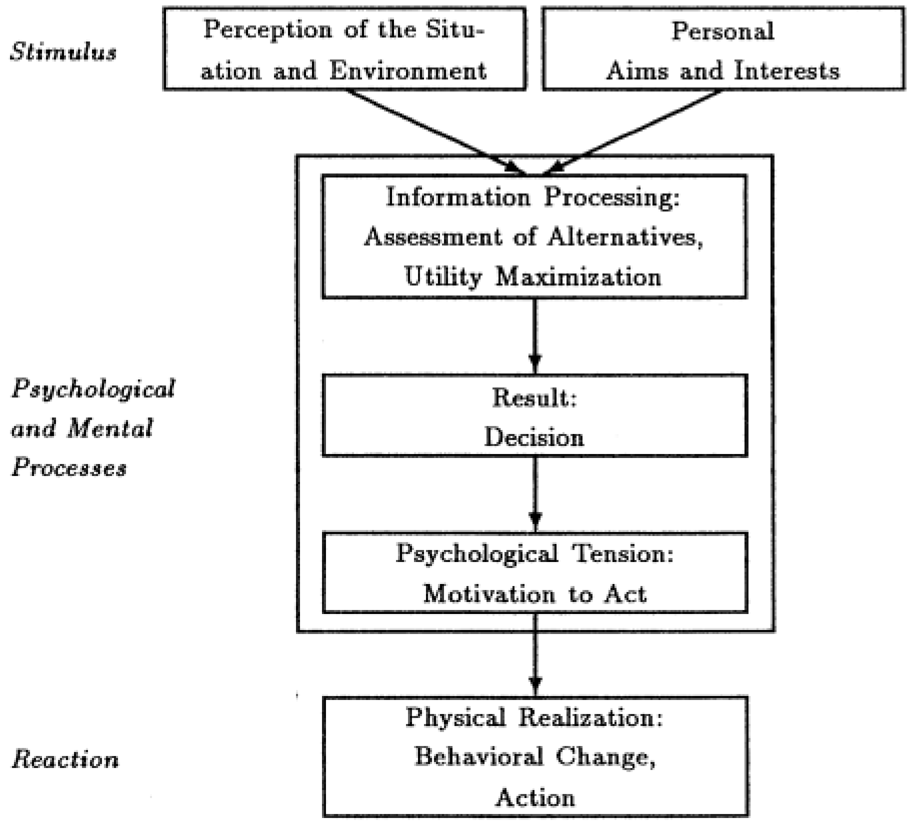


Figure 11. Social Forces processes flowchart leading to behavioral changes (Helbing et al., 2005)

Concluding, we can state that the Panic may affect the overall outcome of an evacuation, it spreads and is dependent on the distribution of the evacuees. It has been observed that populations under panic tend to "clog" more easily, as many evacuees try to rush toward the exits. As shown in Figure 8, the evacuation time is increased as the Desired Velocity is steadily increased (Parisi & Dorso, 2006).

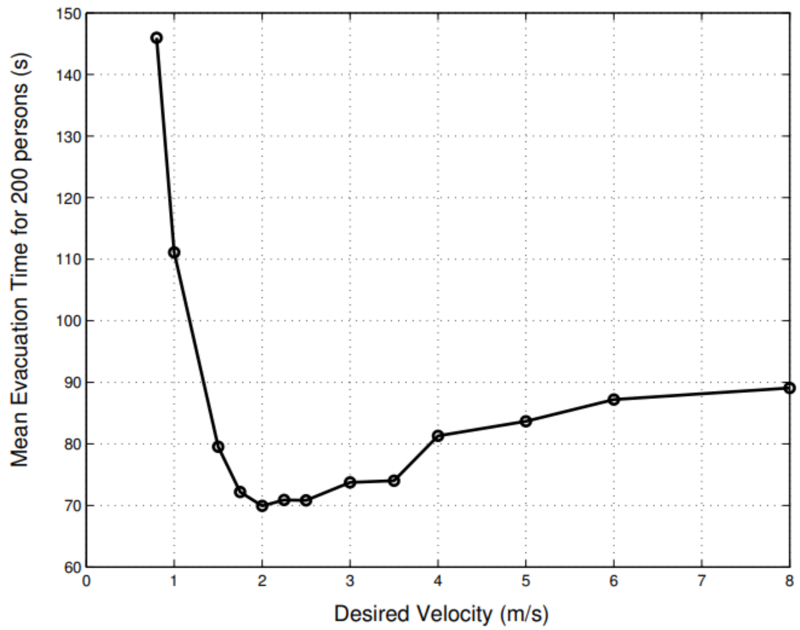


Figure 12. Desired Velocity and Evacuation Time (Parisi & Dorso, 2006)

3.3.2 Affiliation Model

During the early stages of an incident, the evacuees tend to form teams. Individuals are attached to other primary team members and cope with the situation (Sime, 1995). This is a common behavior among members of the same family, relatives, or friends, but may also be observed among strangers. In fact, the group's affiliation at the start of the emergency is an important factor in whether the group stays together or not (Robinette & Howard, 2011). As Sime states (Sime, 1985) the Affiliation Model predicts that in an emergency people are even more likely to be drawn toward the familiar than under normal circumstances. Moreover, experimental studies have shown that participants who stayed as a couple in hotel rooms or participants of groups of high affinity such as families or very close friends, tend to wait for their couples or groupmates, even when the danger is imminent, search for them, in order to evacuate together. This observed behavior is indicative of the Affiliation Model (Kobes et al., 2010). Loosely formed groups without strong ties tend to scatter quicker and to cooperate poorly, as members of the group tend to leave or completely ignore the group. Therefore, the Affiliation Model prevents the evacuees from panicking and prioritizes their social behavior and each member of a group acts as an individual, in contrast to the Panic model, where the evacuees are treated as groups (Mohareb, 2011). The Affiliation Model provides reliable results, as only 0.8% of the total number of evacuees will panic during an emergency (Blake et al.,2004). An analysis of human behavior during the WTC disaster of 9/11 based on published survivor accounts. Concluding, in the Affiliation Model the social ties remain dominant and define the behavior of the evacuees, while they greatly affect the overall outcome of the evacuation.

3.3.3 Protective Action Decision Model

The Protective Action Decision Model (PADM) is a multistage model that is based on findings from research on people's responses to environmental hazards and disasters (Houts et al., 1984; Lindell & Perry, 2012). As Tepstra & Lindell (Terpstra, & Lindell, 2013) state "the PADM was first developed to explain people's protective action decisions in response to imminent disasters (Lindell & Perry, 1992; Lindell, 2013) and was later extended to account for people's long-term hazard adjustments" and has been used to predict the preparedness of people to natural disasters. Kuligowski (Kuligowski, 2013) argues "The Protective Action Decision Model (PADM), which is based on over 50 years of empirical studies of hazards and disasters, provides a framework that describes the information flow and decision-making that influences protective actions taken in response to natural and technological disasters".

PADM describes the decision-making process in which individuals engage prior to performing protective actions during crises. Perceiving cues from the natural and social environment, the subjects will take actions to protect people or property, reducing their stress. Figure 9 depicts the decision-making system of the PADM model.

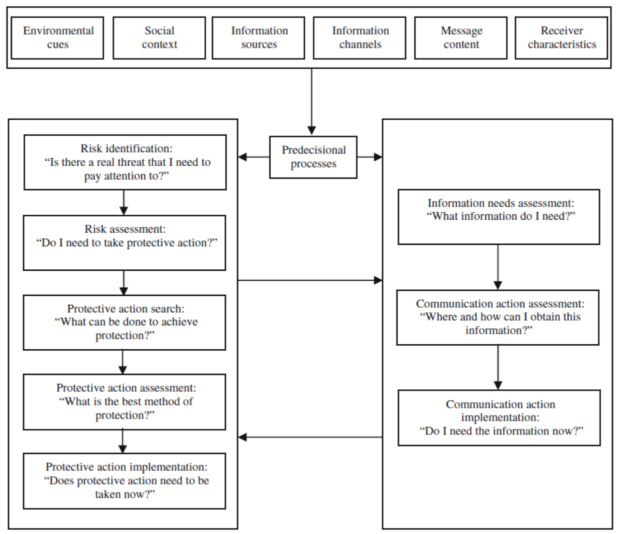


Figure 13. PADM diagram (Kuligowski, 2013)

3.4 Stages of Human Behavior

While not all evacuations end up in catastrophes, there are specific events that may produce behaviors that may potentially drive to unfavorable endings. For the prevention of these disasters, we initially need to review and assess these events and the reactions of the evacuees, during all the stages of an evacuation. Based on the most recent studies mentioned above, human behavior passes through specific stages, when in danger.

This chapter is based on the stages of evacuation as they are described by Vorst (Vorst, 2010), who proposed the more *John Leach's Dynamic Disaster Model* combined with studies on real incidents or drills (Benthorn & Frantzich, 1996; Ramachandran, 1990; Fahy & Proulx,1997; Kuligowski, 2009; Kuligowski, 2013; Proulx & Sime, 1991, Cohn et al., 2006). After reviewing these studies and incidents, the classification of a four-phased model for the description of the progress of human behavior during evacuation is proposed. The stages discussed herein are focused on human behavior and not the actual stages of a disaster, although in most of the cases these stages coincide or have a strong affiliation. Because of this, Table 10 demonstrates the correlation of the Human Behavior Stage and the corresponding Evacuation Stage.

Human Behavior Stage	Evacuation Stage
Information about the Event	Threat
Pre-movement	Warning
Reaction*	Impact – Recoil - Rescue
After the disaster	Port-Trauma

Table 12. Human Behavior - Evacuation Stage Correlation

*The Reaction stage falls under three different evacuation Stages and thus is correlated with all of them.

3.4.1 Phase 1 - Information about the Event

The acquired information is a crucial factor in evacuee's behavior and is perceived by the physical and social environment (Kuligowski, 2013). It is reported that during some incidents the hazards were either not recognized or were ignored even when the occupants had been warned multiple times (Dickie, 1995). The information can be passed directly from phenomena, such as the cracking sound of a fire or indirectly, by a fire alarm. When a hazardous event happens, there is uncertainty about the nature, the volume, the distance, and the imminence of the danger. The precision of the information about the situation, the location, and what is asked from the evacuees to be done, decreases the stress, while it ensures an efficient evacuation (Proulx, 1993). Therefore, a well-informed crowd that is guided toward an exit increases the chances of a safe evacuation with low casualties. In contrast, an unexpected evacuation signaling may lead even to mental disorientation of evacuees (Koo et al., 2014). Although an early alarm sound is significant, if the response is lower than optimal, this means that people think that this may be an exercise or a false alarm (Ramachandran, 1990).

In the past, it has been a common belief that informing the evacuees by voice announcements would provoke panic reactions. However, this misconception led to the opposite results in many cases. Recent studies have shown that voice announcements contribute to the safe evacuation of the occupants. The information by voice about the nature and the location of the incident calms down and assists the occupants during their evacuation (Proulx, 2001, May). Quarantelli (Quarantelli,1975) states that the pre-event acquired knowledge about the hypothetical reaction of other evacuees who face the same situation is influenced by the depiction in films, fiction, and press, that shows panic and irrational behaviors and an exaggeration in the volume of these events, may affect the behavior of the evacuees towards panic.

3.4.2 Phase 2- Pre-movement phase

The time between the perception of the incident and the first reaction is called Pre-movement or Delay Phase. The duration of this phase is not standard and varies according to the subject's psychological and emotional state. Whilst the stage is important, allowing the subject to analyze the situation and act accordingly, a prolonged delay may be dangerous because of the progressive worsening of the situation. Simply, if the subject is stalling for too long, a potential danger could reach it. Reports from real-life incidents claim that the delay time can be up to 11.3s when the incident occurs in large structures or areas.

Occupant Characteristics	Building Characteristics	Fire Characteristics
Profile • Gender • Age • Ability • Limitation	**Occupancy** • Residential (lowrise, midrise, highrise) • Office • Factory • Hospital • Hotel • Cinema • College and University • Shopping Centre	**Visual cues** • Flame • Smoke (colour, thickness) • Deflection of wall, ceiling, floor
Knowledge and Experience • Familiarity with the building • Past fire experience • Fire safety training • Other emergency training	**Architecture** • Number of floors • Floor area • Location of exits • Location of stairwells • Complexity of space/Wayfinding • Building shape • Visual access	**Olfactory cues** • Smell of burning • Acrid smell
Condition at the Time of Event • Alone vs. with others • Active vs. passive • Alert • Under Drug – Alcohol – Medication	**Activities in the Building** • Working • Sleeping • Eating • Shopping • Watching a show, a play, a film, etc.	**Audible cues** • Cracking • Broken glass • Object falling
Personality • Influenced by others • Leadership • Negative toward authority • Anxious	**Fire Safety Features** • Fire alarm signal (type, audibility, location, number of nuisance alarms) • Voice communication system • Fire safety plan • Trained staff • Refuge area	**Other cues** • Heat
Role • Visitor • Employee • Owner		

Table 13. Factors having an impact on Human Behavior in Fire (Proulx, 2001, May).

The social forces play a significant role during this phase. Lovreglio et al (Lovreglio et al., 2014) state regarding the Delay Phase that: "Literature argues that social influences (i.e. informative and normative) may be an important environmental factor during evacuations as a way to deal with the perceived uncertainty associated with these situations".

There are two main decisions a person may take during this phase; either i. to run or ii. to stay and fight. The decision is based on factors such as (i) the existence of exit signs, (ii) a clear exit route, (iii) the time pressure, and (iv) the subject's value system. An exit sign under time pressure may make the evacuees follow a clear route. Alternatively, time pressure coupled with a certain subject’s value system may lead to a fight stance. On top of that, the behavior is affected by the role of the subject and its position in a hierarchy. A staff member or a police officer is more likely to stay and help others than leave, as they perceive this as part of their duties.

Proulx (Proulx, 1993) cites the factors having an impact on Human Behavior during a fire, shown in Figure 10. Regardless of the above options, the *Notify Others* reaction is the tendency of the evacuees to inform others about the incident. A sub-stage between the Pre-movement and Reaction Phase is proposed, because this reaction may appear in both phases. During this sub-stage, there is a chance that panic could spread among the evacuees.

3.4.3 Phase - Reaction

The Reaction Stage occurs when the incident has unfolded and most of the evacuees are aware of the danger and are actively reacting. The Human Factor plays an important role in evacuation incidents. Factors such as anxiety or alcohol consumption can affect the behavior of the evacuees (Vorst, 2010). Several behaviors have been observed during this stage as described below.

3.4.3.1 Social Influence

Humans instinctively tend to evade danger, follow lights, and turn left during dangerous situations (Lee et al., 2003). Except for these initial reactions, there are numerous possible actions an evacuee may take. Most of them are listed below in this chapter. People are influenced by others during this initial phase. This behavior is called *Social Influence* and it is inversely proportional to the distance between people (Nilsson & Johansson, 2009). Simply put, as we distance the evacuees, the cooperative/follow-up behaviors tend to attenuate and the evacuees behave individually, making their own independent decisions. As Ji&Gao (Ji & Gao, 2006) states: "In real life when fire or some other uncontrolled situation occurs in places with a large crowd, chaos or even disaster may occur which often causes severe casualties". That's especially true in places where the internal structure is complicated and exit paths are limited and thus may incur serious casualties as people are unable to successfully track the exits while in panic. We have noted above that the factors that may ignite panic behavior are the imminent danger and the lack of any assistance and/or information. Both factors are present in this situation, instigating panic reactions. Ramachandran (Ramachandran, 1990) also describes the human behavior during fire evacuation: "In the stress of a fire, people often act inappropriately and rarely panic or behave irrationally. Such behavior, to a large extent, is because information initially available to people regarding the possible existence of a fire and its size and location is often ambiguous or inadequate". Another point that verifies the correlation of panic and minimal information. Studies have shown that subjects without previous knowledge of the structure selected asymmetrically the assumed closest route to the final exit. Another aspect is that the evacuees tend to follow the exit routes (especially stairs) of the previously escaping evacuees, a characteristic of the follow-up behavior, with a variant. The variant is that the previously escaping evacuees are not always connected to the evacuees that follow up. The evacuees tend primarily to select the routes considering them being the closest ones, to the final exit route, and to follow other leading evacuees even if these routes are not optimal (Zhu & Shi, 2016).

Only a small percentage of the evacuees seek refuge inside the evacuated structure. Most of the evacuees tend to search for an exit. Even this small percentage is usually forced to seek another place due to its proximity with the hazardous elements (smoke etc) or blocked stairs and corridors. Fahy & Proulx (Fahy & Proulx,1997) argue that the reason for not leaving the area, based on evacuees from the World Trade Center 1993 bombing, where one third remained in place during this incident, because i) they had been waiting for information or instructions, ii) they felt, that it was better to wait or they were told to wait, iii) they didn't know there has been an ongoing disaster, iv) they were helping others to leave the area, v) they had existing health issues, vi) they encountered too much smoke, vii) they were waiting for better conditions, and viii) they were waiting for the fire department to arrive. Evacuees under panic cohere closely and almost do not change their exit route while rushing to an exit. Simulations based on real incidents have shown that the first movement-based reaction has been the gathering in front of exits, forming semicircular arcs where no obstacle is present. Subsequently, the fatalities are significantly increased when the evacuee crowd is in panic. The presence of a leader usually reduces the casualties and improves the evacuation times. Whilst the leader's contribution is significant, in the case of panicked crows the overall casualties and evacuation time are nevertheless increased (Wang et al., 2015). Most importantly, comparing *Case I: non-panic* and *Case I: panic*, the casualties increased from 1.5% to 5.4% and the total evacuation time from 28.4s to 35.3s. A leader (*Case I: panic, leader*) decreases the total evacuation time to 23.9s and the casualties' rate to 0.9%, proving that effective leadership can reduce the casualties by up to 6 times and the total evacuation time up to 11.4s. An interesting observation is that comparing Case I: panic and Case I panic, the leader of the l-exit (left-exit) has better evacuation time. This is attributed to the extra time the evacuees needed to coordinate with the leader and safely exit the structure, as indicated by the significantly lower casualty rate. The results of *Case I* and *Case II* are similar. The difference between these two cases is that *Case I* does not include obstacles, whilst *Case II* does.

Scene	Evacuation time (s)				Steps	Casualty
	l-exit	r-exit	b-exit	Total		
Case I: non-panic	18.4	28.4	19.4	28.4	7562	1.5
Case I: panic	13.8	35.3	9.1	35.3	8268	5.4
Case I: panic, leader	13.9	23.9	14.9	23.9	6668	0.9
Case II: non-panic	23.9	34.9	24.5	34.9	9274	2.0
Case II: panic	15.9	35.1	14.9	35.1	9317	2.6
Case II: panic, leader	22.7	26.6	19.6	26.6	8532	1.1

Table 14. Evacuation Time and Panic (Wang et al., 2015)

3.4.3.2 Denial

Denial exists as a defensive mechanism, accompanied by optimism that the disaster is not as serious as it seems to be. Studies have shown that in cases of flooding in Nederland, respondents expressed their optimism that the next flooding will be lighter, without a profound reason. Victims of previous catastrophes are more sensitive to the signs of disasters, more proactive, and respond faster than people without previous experiences (Zaalberg et al., 2009). *Denial* is also met during harsh conditions. This behavior is mainly observed when the conditions are extremely difficult, a situation is perceived as hopeless and the aid seems unlikely. The subjects go into denial of the emergency's danger. The amplitude of the reactions of the evacuees in denial is wide. It may vary from the lack of interest in the situation to and/or the ignorance of the available information to hypervigilance (Kuligowski, 2013). Denial usually leads to poor judgment and risky behavior. Although Denial is not a positive factor, it has sometimes been observed that the evacuees can use this initial time to better assess the situation and confirm the threat extent and gravity (Cohn et al., 2006). In contrast, some people end up denying the danger outrightly. During the US Wildfires evacuation in 2000 and 2002, residents refused to evacuate their homes, because they wanted to protect their properties with their own means, refusing to obey the local sheriff's evacuation orders.

3.4.3.3 Panic

Continuing from the Panic Model, Panic is modeled according to the Social Force Model (Helbing et al., 2005), which has been described in the previous chapter. The model is defined by the equation of motion ((Li et al., 2014):

$$f_i = m_i + \frac{dv_1(t)}{dt} + \sum_{i \neq j}^{\infty} fij + \sum_{w}^{\infty} f_{iw} + e_i(t)$$

- $\mathbf{f_i}$: the sum of the social forces influencing pedestrians,
- $m_i + \frac{dv_1(t)}{dt}$: the driving force when pedestrians keep desired speeds,
- $\sum_{i \neq j}^{\infty} fij \; and \sum_{w}^{\infty} f_{iw} + e_i(t)$:the repulsive forces describing the attempts to keep certain safety distances to other pedestrians (j) and obstacles (w).
- $e_i(t)$: the individual fluctuations force reflecting unsystematic behavioral variations.

Regarding panic behavior, Li (Li et al, 2014) states that it is not only affected by the emergency situation but by factors such as the occupants' characteristics, environmental conditions, and the response of pedestrians to emergencies. The proposed model recognized three crisis factors: residence time *t*, crowd density *ρ,* and exit distance *d*. The corresponding effects are the non-decreasing f(t), g(ρ), and h(d) functions since the oppressive (panic) feeling among the pedestrians does not decrease during an egress. An assumption states that a critical point of residence time t^L exists in the model and $f(t^L)$ is the corresponding critical degree. If t is lower than t^L, the time is not enough to provoke panic behaviors, if the t is higher than t^L, the panic behavior is meant to occur. The time for panic to occur is defined by the threshold value L_0, based on the below equation:

$$\left\{ L_0 = min(f(t^L),\ g(\rho^L), h(d^L)\ f(t) = \left(1 + e^{-\frac{10.6r}{t^*} - 5.3)}\right)^{-1}\ g(\rho) = \left(1 + e^{-\frac{10.6r}{r^*} - 5.3)}\right)^{-1}\ h(d) = \left(1 + e^{-\frac{10.6r}{d} - 5.3)}\right) \right.$$

- t^L**:** the critical point of residence time (60 seconds), or the evacuees' response time.
- ρ^L**:** the critical point of density is set to 3.33 p/m^2.
- d^L**:** the critical point of exit distance, as the farthest distance to the exit.
- **t*:** the maximum tolerable value of residence time.
- **ρ*:** the maximum tolerable value of density set to 5.0 p/m^2.
- **d*:** the maximum tolerable value of exit distance.

For a pedestrian the *Crisis Level* L_0 is defined by:

$$\left\{ L_0 = a\, x\, f(t) + b\, x\, g(\rho) + c\, x\, h(d)\ a + b + c = 1 \right\}$$

- The a, b, and c are the weighting factors.

Therefore, panic behavior can occur under specific circumstances, and it is not the case for all emergency evacuations. Factors such as the residence time, the density of the evacuee's crowd, and the distance towards an exit, define when and if panic will spread among the occupants.

The next question is what Panic looks like. Nevertheless, many disasters have not been caused by the actual cause, but by the Panic reactions of the crowd or individuals. Panic behavior is divided into Collective and *Individual* (Quarantelli, 2001). Individual panic refers to the panic reaction of one subject and the collective to the contaminated panic reactions of multiple subjects. It is noted that in underground evacuations the first reactions are worrying and herding and only 21% of the evacuees stay calm. Most people explore the area to assess the situation.

The lack of information, the ambiguous situation, the large crowds, the feeling of entrapment, and the low expectation of aid cause increased stress and eventually panic. Not all evacuees under these conditions are being panicked, but this reaction can spread into a crowd and force other evacuees to react mimicking the panicked evacuees. This behavior is usually instigated by evacuees in proximity, while their stay has been prolonged, satisfying the Helbing equations. A typical panic reaction sequence is the abolition of social ties, rushing toward an exit, being unable to change routes (NORRIS, 1987; Sime, 1995; Quarantelli, 1975; Wang et al., 2015). The feeling of "getting lost" in an unfamiliar place led to panic reactions while only one-third of the evacuees will stay calm. Panic affects the female subjects more (46.3%) than the male ones (30.6%) and affects the highly educated more than the lower educated. When the evacuees carry luggage, they tend to be more nervous at a percentage of 70.9 % and become prone to panic. On the other hand, evacuees "stuck" in congestion are characterized by anxiety rather than panic. A critical ascertainment is that less than a third help fallen down evacuees, and especially 41% try to stay as far away as possible from them. (Wang et al., 2016). Most of the evacuees leave the area of evacuation using the entrance they used when they entered the area. The familiar exit is more likely to be selected even if there is a closest open exit. Additionally, an open exit is more attractive than a closed one, and therefore the strategy of opening doors has been adopted (Benthorn & Frantzich, 1996). It has also been observed that fire extinguishers are rarely used due to the difficulties of their use by untrained individuals (Ramachandran, 1990). It has also been observed that, when the evacuees in a typical supermarket evacuation are under panic, are incapable of effectively finding the exits, and are mainly following the evacuees in front of them. (Yang et al., 2005). This behavior has also been observed by Rubinette (Robinette & Howard, 2011), on simulation, especially for groups with High Affinity. One common consequence of this behavior is clogging in front of exits by evacuees that block the entrance with their bodies (Parisi & Dorso, 2005). Figure 12 shows the results of panicked evacuees stuck in front of a door.

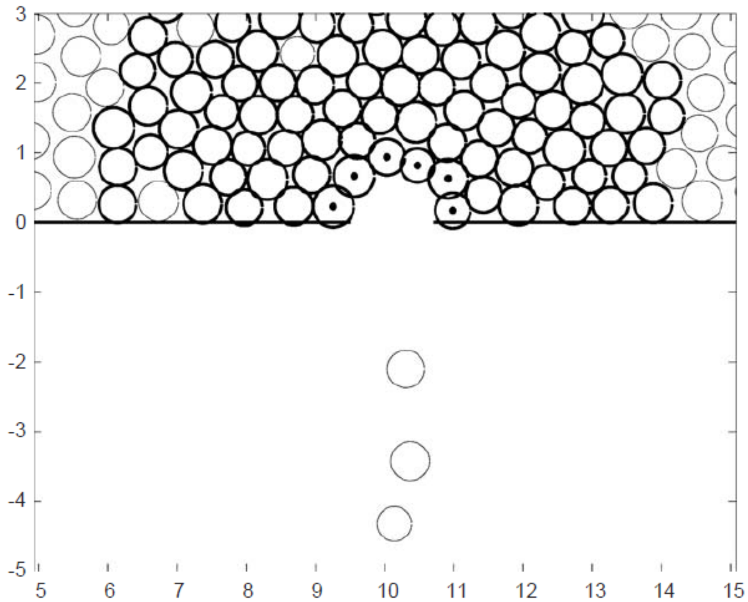


Figure 14. A typical blocking cluster. The blocking evacuees are indicated with a dot. (Parisi & Dorso, 2005).

An indicative example of such an incident is the 1998 *Gothenburg discotheque fire*, which killed 63 and injured 213 teenagers out of the estimated total of 375. The information of the occupants was contradicting and ambiguous, instigating stress and panic. Many of them were intoxicated or disorientated due to the toxic fumes. No fire alarm was sounded, and the warning was ignored. The main exit was partially blocked by a table and panicked teenagers were congested in front of the narrow exit, dying from the toxic fumes and blocking the exit with their bodies (Cassuto, J., & Tarnow, P. (2003). Most of the ADC were present, resulting in a high number of casualties (63/375).

Another factor is the *Panic Spread Time (PST)* (Li et al., 2014), which is the time between the first evacuee that starts to panic until there are no more panicked occupants. PST is not constant or standard and varies between scenarios. For low evacuees' numbers (Figure XIII – scenario 1), no panic behavior is observed, but as the number of evacuees is increased then panic starts to occur ((Figure XIII – scenario 1). The reason for this behavior is that the proximity of the evacuees is higher, lowering the threshold for panic behavior (L_0), enabling more evacuees to overcome it. Figure 13 shows the values of PST and the total number of panicked evacuees, in various scenarios.

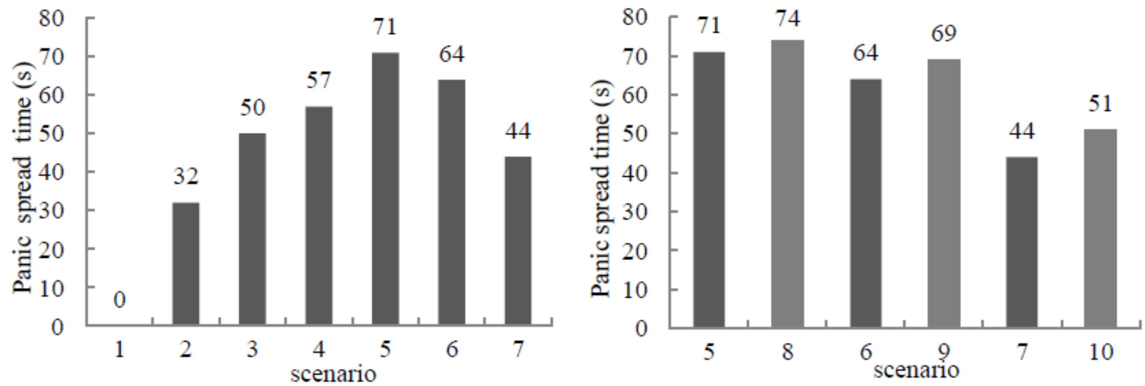


Figure 15. Values of PST and the total number of panicked evacuees (Li et al., 2014)

The variation of the PST means that non all the evacuees are affected by panic. The Panic Rate (PR) (Li et al., 2014), (measures the ratio between the panicked evacuees and their total number. Figure 14 shows a typical behavior. Panicked evacuees are evacuating faster than non-panicked, but as time passes and the number of evacuees is increased, the evacuation efficiency drops due to congestion and bottlenecks.

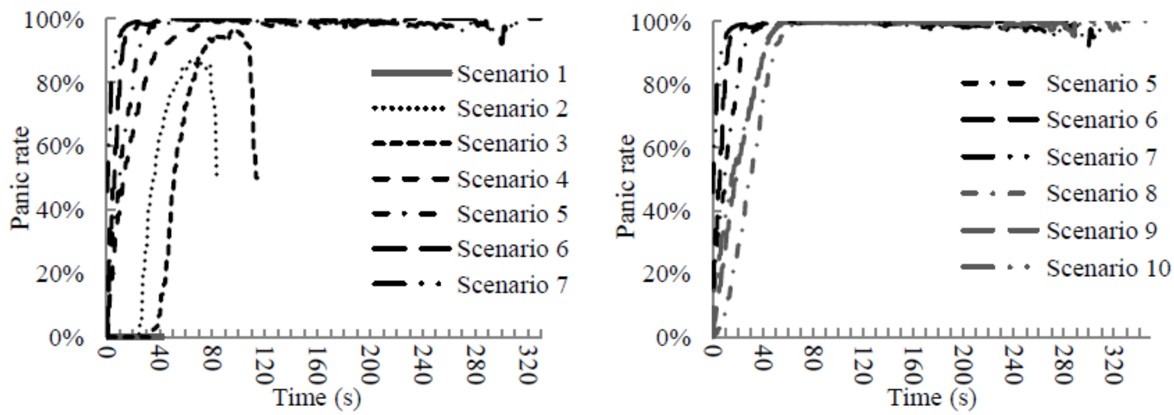


Figure 16. Panic Rate and Evacuation time in different scenarios (Li et al., 2014)

Another aspect of evacuation that is debated in this subchapter is the phenomenon of *Herding*. A crowd of evacuees is divided into three types of people: Calm people, Panicked people, and Herding people. We have found out (Lee et al., 2004) that increasing the density (ρ) of a crowd decreases the panic threshold. Increased crowd density leads to increased group pressure and eventually to a process that is called *Herding-Panic*. Figure 15 displays the correlation between calm, panic, and herding people.

Panic

Weights	Calm people	Herding people	Panic people
Calm people	–	ω_1	Offset
Herding people	$-\omega_1$	ω_3	$-\omega_2$
Panic people	Offset	ω_2	–

Figure 17. Correlation between calm, panic and herding people (Wang et al., 2017)

The same connections between individuals have the same Influence Weight (IW). In the above diagrams, the IW is symbolized as ω1, ω2, and ω3. Based on that, the figure has been created, which represents all the correlations as a Relationship Network. Therefore, three equations that represent the IW between the three types of evacuees have been created:

- IW from Calm people to Herding people:

$$\omega_1 = \omega_{im} = \alpha \frac{(k_i k_m)^{\theta}}{(k^{\theta})^2}$$

- IW from Panic People to Herding people:

$$\omega_2 = \omega_{jm} = \beta \frac{(k_j k_m)^{\theta}}{(k^{\theta})^2}$$

- IW between Herding people:

$$\omega_3 = \omega_{mm} = \gamma \frac{(k_m k_m)^{\theta}}{(k^{\theta})^2}$$

(The Equations have been retrieved from Wang (Wang et al., 2017) to describe the changes to human behavior.)

Where:

- **i:** Calm people.
- **j:** Panicked people.
- **m:** Herding people.
- **α, β, γ:** Weight coefficient of Calm people, Panicked people, and Herding people respectively.
- **k_i**: The degree of node i.
- **k_j:** The degree of node j.
- **k_m:** The degree of node m.
- **k:** The average degree of the network.
- **θ**: a constant index of a specific weighted network, where $0 < \theta < 1$.

In the above model, Herding is treated as a decision-making stage and the models change as some of the Herding evacuees eventually become Panicked and others will become Calm, which is decided by a

Threshold Model. This revised panic model is named Herding – Panic and when the Threshold is exceeded the Herding people become Panicked. As the amount of pressure is mounting, the Threshold is reduced and the Threshold can be reached mainly due to external pressure to the herding people by already panicked evacuees, as time passes. The Threshold model is mathematically represented as shown below:

$$U_{i,t} = a_i A_{i,t} + b_i B_{i,t-1}$$

Where:

- $U_{i,t}$**:** the utility of Herding – Panic Behavior perceived by the *i*th people at t time.
- $A_{i,t}$**:** the initial utility perceived by Herding people per se about the panic behavior.
- $B_{i,t-1}$**:** the cumulative effect of the evacuation crowd network on the *i*th Herding people at time t-1.
- $\boldsymbol{\alpha_i}$**:** a coefficient that defines the degree of certainty of $A_{i,t}$.
- $b_i B_{i,t-1}$**:** the group pressure of the network to the herding people.

If the herding – panic utility threshold for Herding people is set to 0:

- When $U_{i,t} > 0$, the ith herding people will become panicked in time t and $\varepsilon_{i,t} = 1$.
- When $U_{i,t} < 0$, the ith herding people will become panicked in time t and $\varepsilon_{i,t} = 0$.

A Herding evacuee is emotionally unstable, relying on the behavior of others when facing emergency situations. It is mostly observed in situations that the evacuees form large groups rushing uncontrollably towards an exit. Herding behavior is an irrational reaction and leads to overcrowding, slower escape and increased casualties (Helbing et al., 2002). High Herding produces vying behaviors even in non-urgent situations (Zheng & Cheng, 2011). In general, a common pattern on evacuation behavior is proposed by Lee et al (Lee et al., 2003):

- People move or try to move considerably faster than normal.
- Individuals start pushing, and interactions among people become physical in nature.
- Moving and passing a bottleneck becomes uncoordinated.
- Escape is further slowed down by fallen or injured people acting as obstacles.
- People show a tendency towards mass behavior, that is to do what other people do.

In contrast, Meng (Meng et al., 2019) states that when the visual field of the evacuees is clear the herding evacuees escape faster, compared to simulations without a clear field of view. The field of view can be obstructed by smoke, fire, overcrowding, or any other element and therefore Herding could be worsening the evacuation efficiency in most real-life evacuations. Strategies for suppressing herding can be environmental and exit strategies (Zafar et al., 2017), as it has been observed that two the existence of two exits reduces panic and therefore the herding behavior. In spite of the effect of human psychology on the behavior of evacuees, the above-mentioned results have shown the important impact of social influences, spatial events, hazardous elements, and structural elements during evacuation.

3.4.4 Stage 4 - After the Disaster Behavior Stage

The After the Disaster Stage describes the behavior of the evacuees after the disaster. The danger has passed, and the survivors try to start over and return to their homes (Vorst, 2010). The immediate measures could be social and psychological support for the survivors (Zaalberg et al., 2009). This stage is out of the context of this study, as it does not fall under the discussion on evacuation.

3.5 Evacuation Factors

Although the above-mentioned stages clearly describe the stages of human behavior during an egress, there are contributing factors. Studies have shown (Sorensen, 1991; Gershon et al., 2007) that specific factors, such as the response time, the type of the threat, the constraints, the warning systems, the width of staircases, the illumination of the area, the training of the employees and the social structure, affect the overall outcome of an evacuation. Another component (related to the social structure mentioned before) is the Human-related factors, such as the recognition of an alarm and the threat itself, the acquisition of information, and the commitment to another task. group behavior (Hofinger et al., 2014). After reviewing these factors, they have been grouped into three main categories: Movement-based (M), Behavior-based (B), or Hybrid (H). Spatial elements are related to the evacuated area, Behavioral study of the occupant's behavior and Hybrid combine both. The Evacuation Factors are listed in Table XXXX based on their Spatial or Behavioral nature. Hybrid elements have been indicated with X in both categories.

	Congestion	Counterflow	Leadership	Bottlenecks	Alarms and Exit Signs	Smoke/Gas
Spatial	X	X		X		X
Behavioral		X	X		X	X

Table 15. Evacuation Factors Categories

The Evacuation factors are described in more detail below. The factors and their modeling methods are described, accompanied by examples and experimental data.

3.5.1 Counterflow - Deference Behavior (M)

Many people move against the mainstream of the evacuees. This flow is called Counterflow or Opposite-Flow and as a result, it reduces the evacuation speed, due to the increased congestion, even if this counterflow is attributed to crew members, that is moving against the main passengers' flow, for reaching and helping other occupants (Yoshida et a., 2001; Tofilo et al., 2014). The Counterflow effect is usually assessed based on the density of the evacuees (Cłapa et al., 2015). As the two opposing flows meet, the average density is high, and after they meet it starts to rise. Although, in narrow areas, the density is expected to increase and the speed to drop. Experimental data has shown that an ascending flow of Firefighter, who encounter an opposing flow of evacuees, are slowing down as the density of the evacuees' increases. Therefore for 4 evacuees/m2, the firefighters' speed was 0.55 m/s, for 2 evacuees/m2 was 0.58 m/s. for 1 evacuee was 0.89 m/s. The firefighters' speed is maximized when there is no opposing flow to 1.02 m/s. Figure 19 depicts a typical counterflow movement.

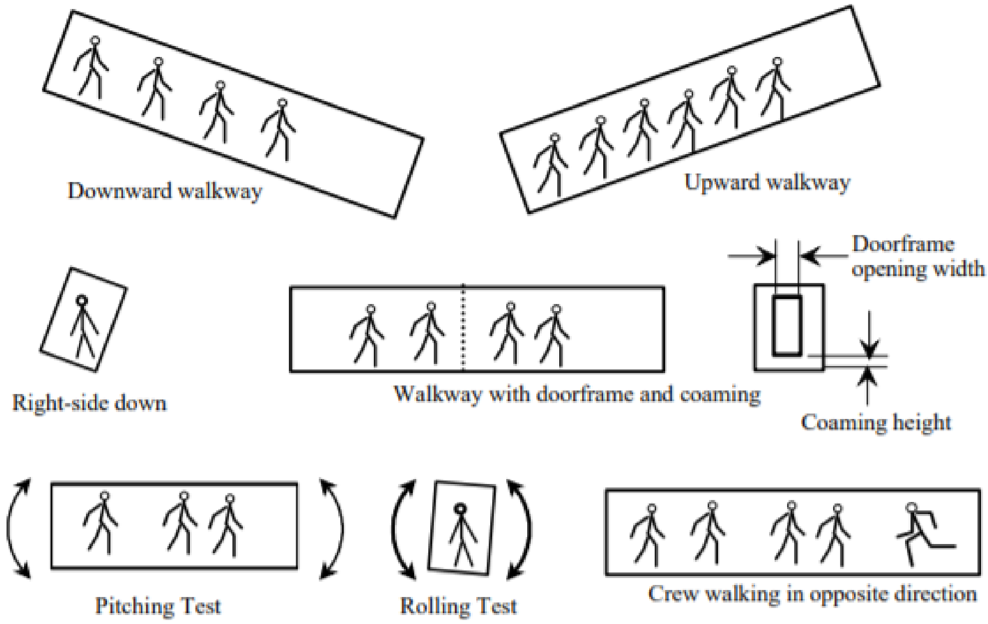


Figure 18. A typical counterflow movement (Yoshida et al., 2001).

Deference Behavior (DB) is the meeting of a flow of evacuees with another flow moving toward and against their path. This behavior leads to a reduction of movement speed and even blocks the occupants who are close to an exit, to evacuate (Pauls, 2004, September).

3.5.2 Leadership – Social Influence (BB)

Another type of grouping behavior is the tendency to follow a Leader. This behavior is attributed to the effect of a factor that is called Social Influence. Social Influence is prominent during the initial phase of an evacuation, and it is increased as the distance between people is decreased (Nilsson & Johansson, 2009). Because of Social Influence people tend to be affected by others and act mimicking or following them. This behavior is the basis of the Leadership phenomenon. The crows are divided into Leaders and Followers. Leaders may be crew and rescue team members or other evacuees of higher status than the Followers. It has been observed that effective leadership inspires the orderly movement of evacuees, even under panic conditions (Wang et al., 2017). Trained leaders (Crew and Rescue Team members) are more efficient than others, accelerating evacuation time by up to 100%. Untrained leaders (Adult family members, evacuees of higher status, or random evacuees) accelerate the evacuation time from 50% to 100%. Therefore, even untrained leaders may achieve remarkable results competing even with the contribution of trained ones, but not as frequently. Some evacuees are more capable of handling difficult situations by nature and thus it is more suitable for them to become leaders (Pelechano & Badler, 2006). Another aspect of Leadership is the sufficient number and distribution of leaders. If the number of leaders is low and is not distributed to the whole evacuated area, then the evacuation efficiency drops, compared to evacuations without any leaders (Hou et al., 2014).

Commonly, family members are gathered and evacuated together and a parent or an older member becomes the leader. Leaders usually positively affect evacuations but the presence of numerous leaders reduces the evacuation performance due to the resulting confusion (Ji & Gao, 2006). On top of that, in case of evacuations, in places where the majority of the evacuees is consisted of families, such as passenger ships, airplanes, and supermarkets the evacuees' flow is not coherent and the initial evacuation time is increased as the family member are first searching and then are joining their families and then they are attempting to evacuate. This behavior can be observed, in the form of large gatherings, wandering, and jamming near the exits. Yang (Yang et al., 2005) states that the cohesion of a group can be measured by its *Kin Attraction*. As the Kin Attraction is increased, the group's cohesion is increased and their distance is usually decreased. Groups with high Kin Attraction, such as families, tend to form groups of three, four, five, or more members and as they are moving as a block, are worsening the congestion near exits and are contributing to long queues. A general conclusion could be that while the number of subgroups is low the evacuation efficiency is unaffected, but as the groups are increased the efficiency is significantly reduced. This observation is depicted in Figure 20 (a), (b), which shows the correlation between Kin Attraction (attract coefficient) and Evacuation Time (time step).

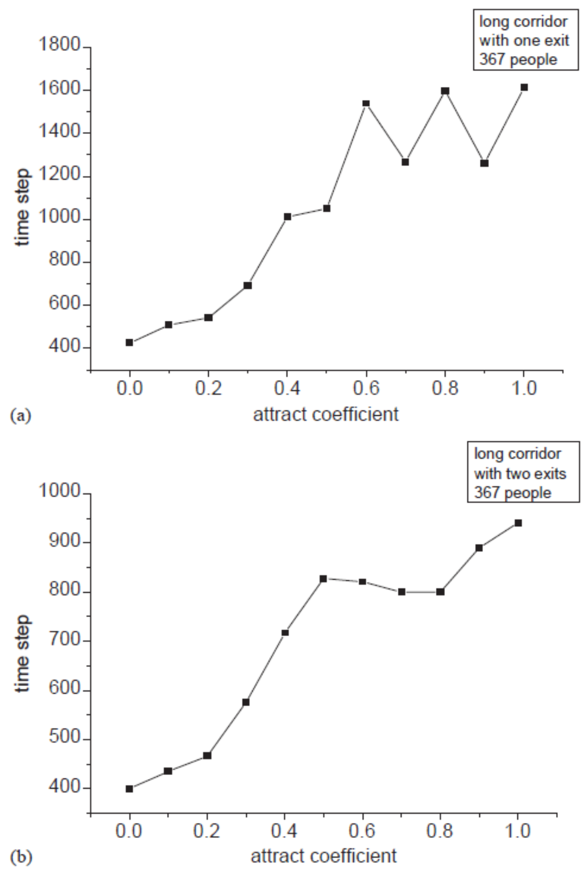


Figure 19 (a) and (b). Kin Attraction and Evacuation Time Correlation (Yang et al., 2005)

Whereas studies have shown that sometimes a leader is not a high-esteemed person, but a random evacuee that accidentally proceeded to the crowd. The crowd tends to follow the evacuee in front of them, regardless of their affiliation (Ding & Sun, 2020).

3.5.3 Bottlenecks (SP)

During evacuation due to a fire or an explosion the Bottleneck coupled with the evacuation time, are the two key factors that affect the evacuee's survivability. During the pick of an evacuation (see Figure 20), when the crowd is rushing toward an exit and the pressure reaches its highest, the bottleneck effect usually appears. As the volume of the evacuated crowds and the speed of evacuation increases, the phenomenon grows larger as more and more evacuees rush to narrow exits (Yi-Fan et al., 2011).

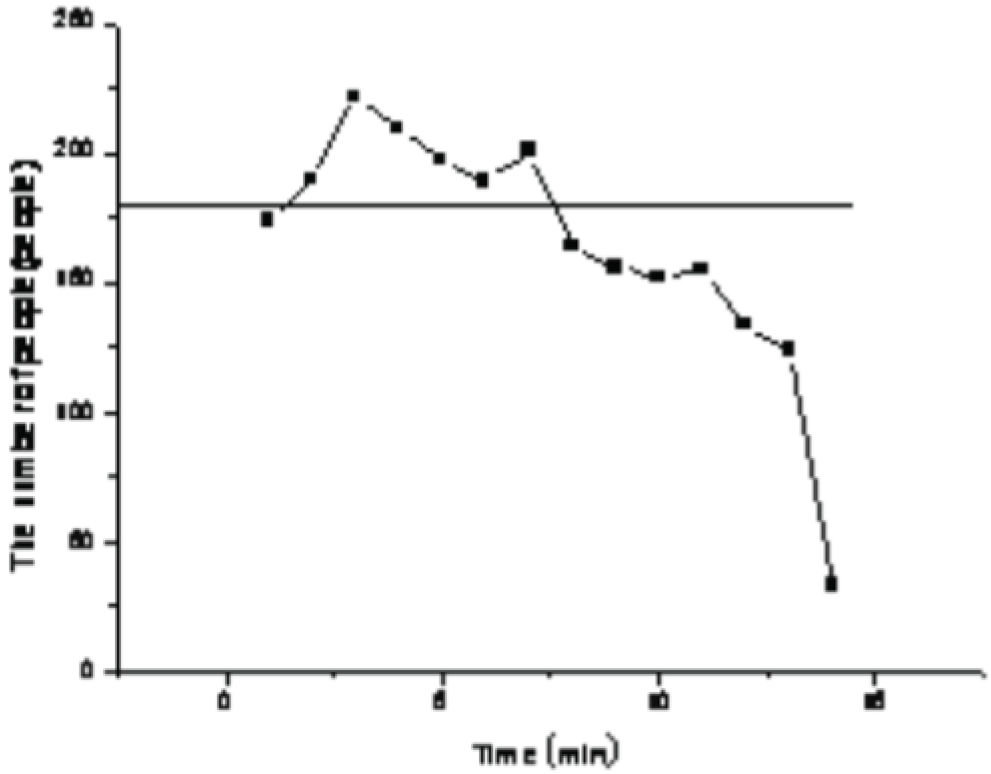


Figure 20. Evacuees number - Time correlation (Yi-Fan et al., 2011)

Another contributing factor for the appearance of the bottleneck effect is the effect of staircases. Though the evacuees slow their speed down, the area is narrower, significantly restricting the movement. Studies have shown that wider staircases decrease the bottleneck phenomenon (Yi-Fan et al., 2011). Moreover, the presence of obstacles may reduce the probability of bottlenecks if the evacuated structure is spacious. If the evacuated area is restricted the presence of an obstacle reduces the evacuation speed, increasing the congestion and the probability of a bottleneck (Lin et a.l, 2019).

As Tanimoto (Tanimoto et al., 2010) argues "a bottleneck situation, where many pedestrians rush to an exit, causing a drastic breakdown of outflow flux from the exit owing to "human jam effect", sometimes referred to as the "human arch" effect". The concentration of high numbers of people on entrances and exits is a repetitive pattern of crowd disasters (Sime, 1995). The flow breaks down and a jamming effect is created. Bottlenecks affect the behavior of the evacuees inside and the evacuees in the immediate proximity of the crowd as well as the evacuation time and the moving speed and the locomotion of the evacuees. Older methods of bottleneck identification have been the Observation method. This method introduced errors due to the quantitative difference and the different infrastructures that produced differentiated results. Nevertheless, their studies investigate the level-of-service for stairs and the velocity-density correlation. With the development of computer technology, more quantification methods were prioritized, providing us with vivid animations, where the bottlenecks could be easily identified (Ma et al., 2014). For identifying bottlenecks, Ma proposes a model that implements a network representation of a building as shown in figure 22.

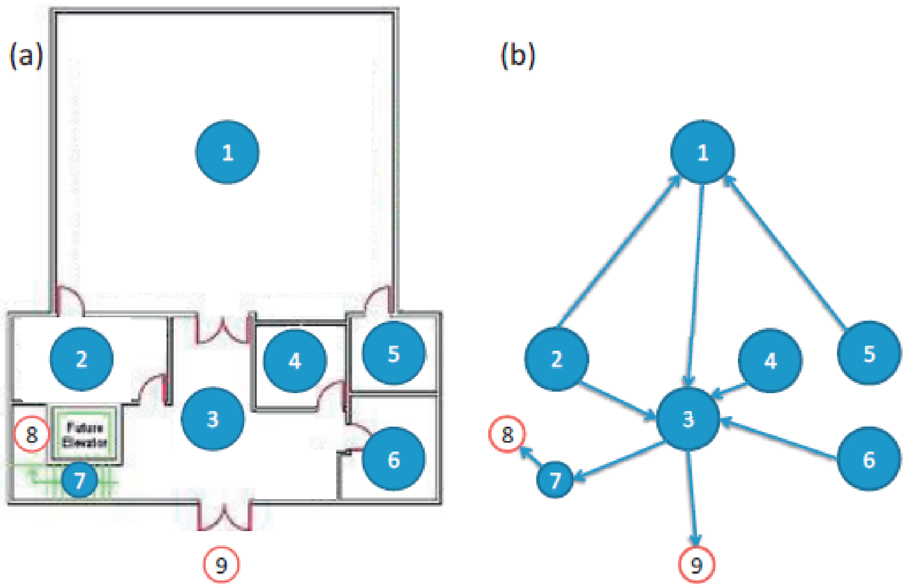


Figure 21. Illustration of (a) a typical building plan and (b) its network representation (Retrieved by Ma et al., 2014).

The principal data requirements for the above graph network are node capacity, node initial contents, connection flow capacity, and connection transit time. The next step is to model the occupants' routing behavior. For the constructed network G(N, E), where N represents nodes and E represents connections, is assumed that the sets of Origin to Destination (OD) pairs, representing from room to the final safety zone, have n_w elements. In the OD pairs, possible paths are connected denoted with P. There are n_p possible paths in the network. The d_w represents the demand of the OD pair w.

First, the evacuation time is calculated based on the equation below (d_w is constant):

$$\varepsilon = \varepsilon(G, d_W)$$

Based on the above the bottleneck probability is calculated based on the below equation:

$$I(g) = \frac{\Delta\varepsilon}{\varepsilon} = \frac{\varepsilon(G-g,\ dw)-\varepsilon(G, d_w)}{\varepsilon(G, d_w)}$$

Where G – g is the network after component g has been removed. Therefore, if I(g) > 0, the degraded network performs the impaired function of the evacuation, and g is expected to be a bottleneck. If I(g) < 0, g is redundancy and should be removed to improve the network's efficiency.

3.5.4 Congestion (SP)

Wang (Wang et al., 2015) describes the phenomenon of Congestion as: "In the normal evacuation process, all the agents only need to arrive at the exit as soon as possible and there is no overtaking. In the congestion evacuation process, some agents want to move to the exit quickly by crowding other agents. Since under intense stress people try to move faster than normal, the overtaking and casualty phenomenon usually arises. The congestion phenomenon is very common in an emergency". The subsequent phenomena inside a congestion area evacuation are listed below:

- The pedestrians gather in front of the exits spontaneously.
- The pedestrians form an arched or semicircular shape close to the exit, a phenomenon called Arching or Clogging (Almeida et al., 2013).
- The pedestrians with strong leadership capabilities can take action by their own expectations, while others will be left to be guided.
- The casualties may increase due to the congestion and the panic.

Chu (Chu et al., 2017) proposes a network model, where the density of a room is defined by the ratio of the number of occupied cells to the number of cells in the room. A density value from 0 to 1 is assigned and it is applied as a penalty to the evacuees that pass through the congested area, simulating the congestion effect based on the below equation:

$$\{\alpha D_t,\ \ if\ Dt \geq \tau,\ \ 1,\quad otherwise$$

Where:

- $\mathbf{D_t}$: The Density of the room at time step t,
- **τ:** the congestion threshold,
- **α:** the penalty for complete evacuation.

When the room is congested (threshold is reached), the link within the room is penalized, by multiplying the costs with αD_t.

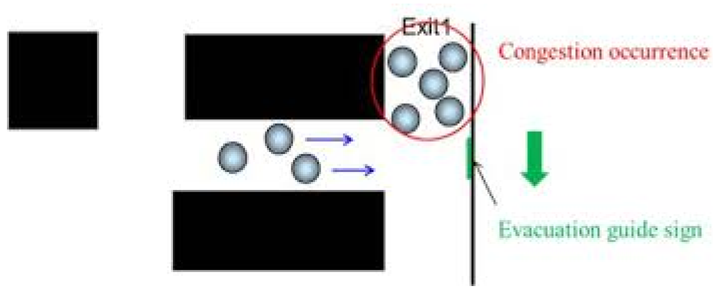


Figure 22. . Congestion (Horii et al., 2019).

Another characteristic of a congested crowd near exits is the formation of an arch, known as Arch Formation-based congestion (Li, & Han, 2019). Arch formation-based congestion alleviation for crowd evacuation. The bodies of the evacuees form an arch (see the dark grey circles in Figure 22) in front of an exit preventing the evacuees behind them from passing through the exit. This is an example of the combination of the congestion and the bottleneck phenomena.

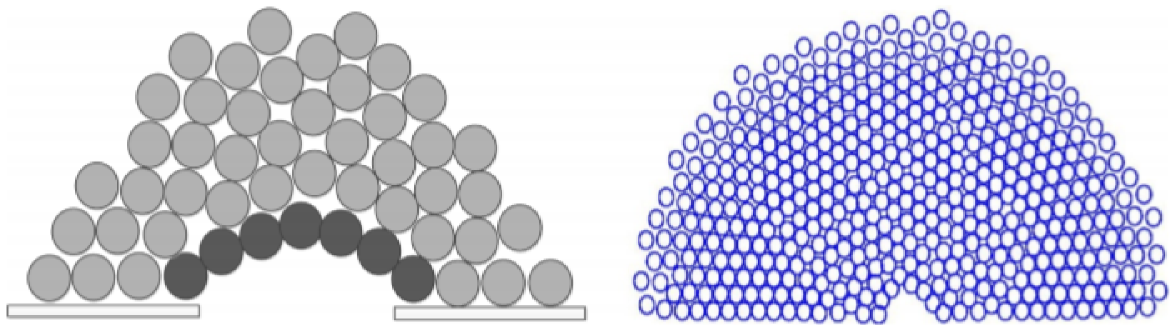


Figure 23. Bottleneck Illustration (Li & Han, 2019)

3.5.5 Alarms and Exit Signs

The impact of placing of Alarms and Exit Signs is considered of the utmost importance. Evacuation studies have shown that most of the evacuees follow the exit signs (75%) but their percentage drops when smoke is added to the area (65%). However, a percentage of 25% to 35% won't follow exit signs because of their wrong placement (placed too high), their wrong interpretation by the evacuees, and the perception of evacuees that their judgment is more accurate than the signs (Kobes et al., 2010).

Visibility is the ability of an observer to see and identify a sign, at a distance in terms of the height of the content of an exit sign. The visual distance is calculated by the equation below:

$$L_2 = L_1 \frac{h_2}{h_1}$$

Where:

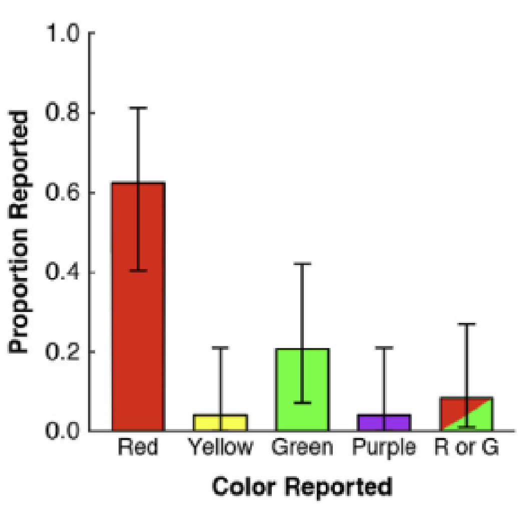
L_2 (m): The Visual Distance,

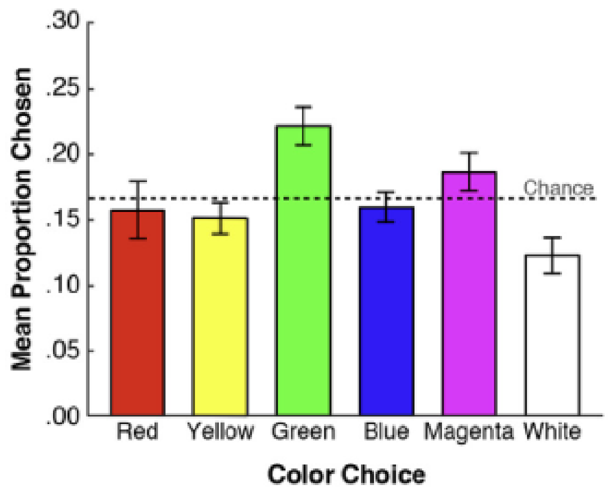
h_2: the height of the sign,

h_1: the measured height,

L_1: the measured visual distance.

Signs with the English word EXIT tend to be more visible to people, as it is easily identified (Wong & Lo, 2007). It has been observed that signs of higher luminance and of red color are more visible than the ones of low luminance and of other colors, especially in smoke conditions (Collins et al., 1990). Nevertheless, other studies state that people tend to follow green-colored signs instead of red ones, during an evacuation (Kinateder et al., 2019).





Elements such as smoke that can obstruct visibility decrease the visibility of signs, but signs with low luminosity are not clearly visible regardless of the presence of smoke or not (Collins et al., 1992). The distance and the spatial configuration of exit signs do not significantly affect the evacuation speed, but in contrast, experimental data has shown an increase to the evacuation speed, when the signs are large and the visibility clear (Jeon et al., 2019).

Verbal messages are assisting the evacuees, by guiding them on where to go and informing them about the situation, although a problem may occur if the evacuees do not understand the announcement's language (Benthorn & Frantzich, 1999).

3.5.6 Smoke and Gas

Studies have shown that evacuees moving in Smoke-filled areas (even in light smoke) are suffering from mental instability (increased unrest, difficulty of thinking) while they struggle to move. The human speed in smoke-filled areas is reduced due to eye and throat irritation and the drop of visual acuity (Jin & Yamada, 1989; Jin, 1997). Moreover, the evacuees may stick to their ideal path and move toward the walls to acquire a form of guidance (Gwynne et al., 2001). Experimental data verify the above-mentioned claims, as stated by Ronchi (Ronchi et al., 2018), the evacuees' average speed into smoke-filled areas is 1.2 m/, while in smoke-free areas this speed is increased to 1.6 m/s. Moreover, the maximum evacuees' speed is reduced linearly, according to the logarithm of the extinction coefficient of the smoke (Seike et al., 2016), as shown in Figure 25. Therefore, an increase in the smoke's density, coupled with the presence of fire and a large crowd, makes the evacuation more difficult (Zheng et al., 2017).

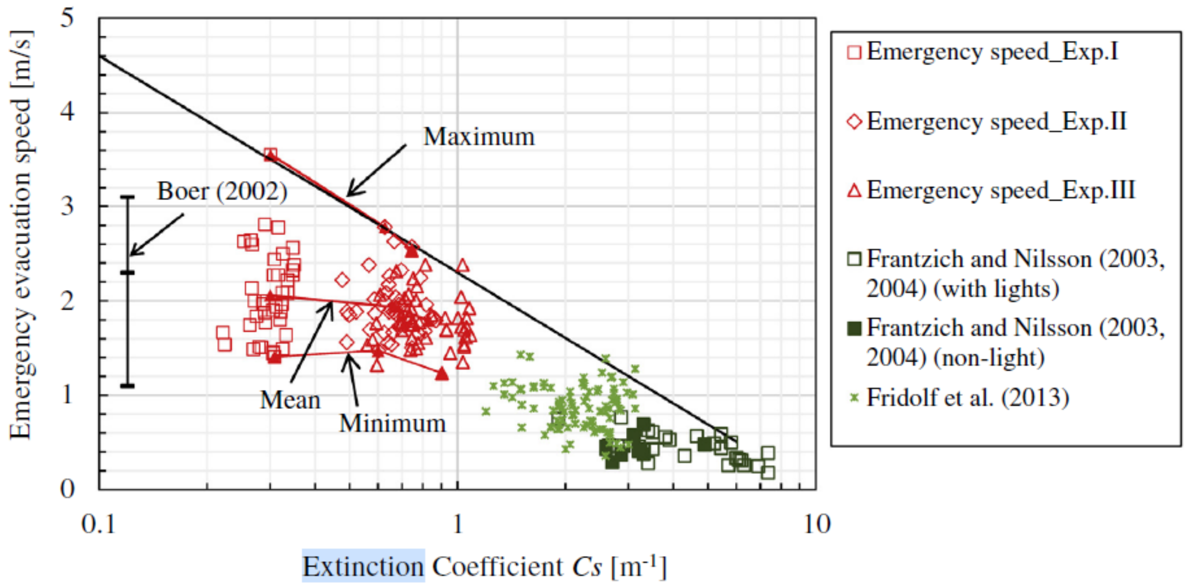


Figure 26. Extinction Coefficient (Seike et al, 2016).

In contrast, it has been observed that when the smoke is visible, but far away from the evacuees, they tend to move faster (avoiding the smoke) toward an exit. When the evacuees are placed in smoke-filled areas, they are more likely to evacuate from the Fire Exit (64.1%) than the Main Exit (Kobes et al., 2010).

3.6 Implementation Factors

The factors that are referenced in this chapter are applied to the Serious Game/Simulator to improve the playability, the user immersion, and the overall gameplay of the application. Gamification and Edutainment contribute towards these goals affecting decisively the user experience.

3.6.1 Gamification

The element of Gameplay Experience (GEx) is prominent in this work. The user does not just participate but actively constructs the experiences (Ermi & Mäyrä, 2005). Therefore, the users contribute to the flow of an evacuation simulation, by participating and interacting with the other evacuees and the structure. In addition to all the above-mentioned Evacuation Models, the Element of Gamification, as a part of the User Experience, also plays a significant role in this research. The difference between GEx and Gamification is that Gamification is Gameplay Experience plus Gamer Characteristics (Örtqvist & Liljedahl, 2010). and this is one of the fundamental concepts of this work. How can the User contribute to the Evacuation Process with their background and experiences?

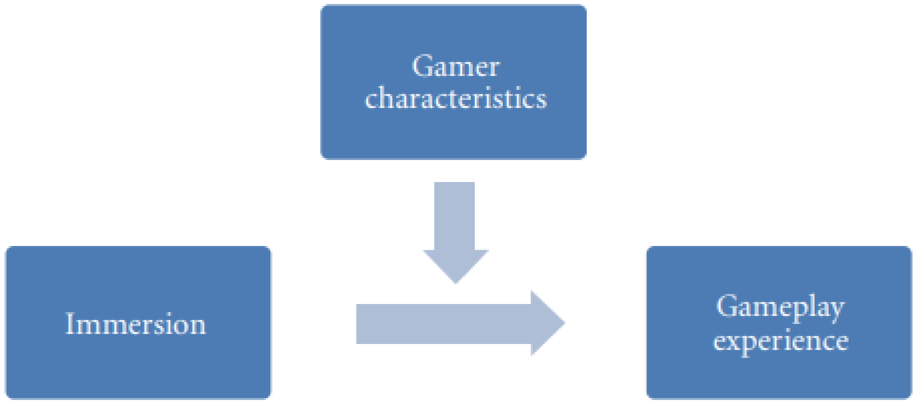


Figure 27. Immersion/Gameplay Experience relevance diagram (Örtqvist & Liljedahl, 2010)

Gamification is the application of game design elements to non-game contexts, to motivate, engage and increase the user's productivity and enjoyment (Deterding et al., 2011) (Seaborn & Fels, 2015), whilst the user is immersed in the virtual world. The final stage of Gamification might be Gamefulness and in fact its final goal (Deterding et al., 2011). Gamification is not only applied to simulators but to multiple fields such as Healthcare (Kerfoot & Kissane, 2014), improving the performance of medical residents during surgical operations, Education (Miller, 2013; Pirker & Gütl, 2015) enhancing the knowledge of the students, Service Marketing (Huotari & Hamari, 2012, Huotari & Hamari, 2017) setting the customer to the center of the process and in literally every possible concept.

User Immersion (UIm) describes the different levels of user experience while playing a game. UIm is closely related to the realism of the game world or to the atmospheric sounds, although it is not always achieved, even if a game has high-end graphics and realistic sounds. Users experience different levels of immersion that start from Engagement (lowest level of involvement) to Engrossment, and eventually to Total Immersion, where the users are cut off from reality and are immersed in the game (Brown & Cairns, 2004). UIm is deeper when the application is not displayed to regular displays, but via Virtual Reality HUDs. The VR users act faster, whilst their performance was worse when they returned to traditional displays. The application of Virtual Reality requires computer graphics of the highest quality as its low-quality computer graphics, will produce a huge difference from reality, ruining the experience (Dhaya, 2020). As Virtual Reality is a destination and not solely a technology, the users react differently and Immersion is achieved via multiple elements such as the controls, the virtual world, or the context (Harth et al., 2018).

For the successful application of Gamification towards the goal of Total User Immersion, the stages proposed by Aparicio (Aparicio et al., 2012) we followed (IJsselsteijn et al., 2007):

- **Identification of the main objective:** for this study, the main objective is to assess the application of Gamification to Evacuation Simulators.
- **Identifying the transversal objective:** Games usually like to survive through challenging tasks and therefore they are continuously provided with such.
- **Selection of game mechanics:** Positive feedback, challenges, and messages are provided to the users.

- **Analysis of the effectiveness:** This factor will be presented in Chapter 5 when the Ship Evacuation Simulator will be introduced.

Gamification in Evacuation Simulators should not be applied only by providing the users with small rewards, such as budgets, and adding them to leaderboards, as those elements are not the core of gamification (Seaborn & Fels, 2015). Peer-approval rewards are also the target of a simulation.

3.6.2 Edutainment

Games have been a universal learning tool for children and adults, allowing them to acquire knowledge in the most natural way (Rapeepisarn et al., 2006). Learning from media has been around for decades, starting from educational TV and culminating in educational games (Egenfeldt-Nielsen, 2011), and similar terms such as infotainment and technotainment belong to the same category. Edutainment thrives in a computerized environment, though it can also be found on films, music, multimedia, websites, and television programs, while it can fully implement video, image, sound and other multimedia in computer applications, providing the learners with a complete learning approach (Aksakal, 2015). The combination of gaming elements such as Competition and Goals, Rules, Choice, Challenges, and Fantasy, with educational content, but only under specific pedagogical elements to avoid the development of a game only for entertainment (Charsky, 2010). Edutainment computer applications may immerse the user in the virtual environment producing a phenomenon similar to the immersion produced by gamified simulators and computer games, contributing to the increased involvement of the users in the educational process, creating an ideal combination of entertainment and education (Addis, 2005). Moreover, it has been observed that students of different cognitive levels have been encouraged to focus on their studies. Through Edutainment the teaching is centered on the learners' needs, complex topics can be taught more effectively, increasing the motivation of the learners (Veltman, 2003). A method to improve the user experience, involvement, and immersion is the challenge and curiosity, which gives a clear advantage in contrast to simple instructions.

3.7 Behavioral Models, Serious Games, and Simulators

The previously referred evacuation factors can be modeled mathematically and this is the first step for creating algorithms that implement them in Evacuation Serious Games/Simulators. The application of the evacuation factors to Evacuation Serious Games and Simulators. Moreover, especially in complex cases, implementing the *Human Factor* gives an ideal opportunity to find unlikely combinations of factors that could lead to disasters during evacuations (Vorst, 2010). Kuligowski (Kuligowski, 2003) argues that: "The simulation computer model should be able to predict individual behavior and group dynamics that are likely to occur in a building fire, rather than relying on ad-hoc user-prescription". Subsequently, the development of an effective behavioral algorithm that includes psychological factors of the computer-controlled evacuees is considered the core of the simulator, as it controls all the functions of the simulator, even indirectly, as it affects the overall outcome of the evacuation.

This can be proven by the lack of the modeling of the psychological factors on evacuation drills. In contrast to simulators, the cases of extreme conditions are not generally tested and the observations are based on normal conditions and exercises (Kluepfel, 2003). As panic reactions must meet certain conditions all other reactions are generally based on rational thoughts. As a result, "Most models lack an understanding of the social psychological and social organizational dimensions of emergency evacuations" (Santos & Aguirre, 2004).

Many evacuation simulators and models aspire to simulate human behavior. The first example is the EXODUS simulation program, which incorporates a complete set of twenty-two social-psychological attributes and characteristics for each agent. Some of them are age, name, gender, breathing rate, running speed, dead/alive, etc, and also the agents possess a fixed degree of familiarity with the building, agility, and patience (Santos & Aguirre, 2004).

Another example of the inclusion of panic behavior in a computer simulation is a multi-agent microscopic model proposed by Wang which proposes the accounting of the impact of multiple computer-controlled agents, panic behavior, and leadership contribution (Wang et al., 2015). Shiwakoti (Shiwakoti et al., 2009) also presents a hybrid model of the collective motion of pedestrians based on animal dynamics and molecular dynamics. They claim that the results are to be confirmed by post-evacuation data. Shiwakoti et al claim that their model reproduces the behavior of pedestrians and that modeling and empirical study of pedestrian behavior under emergency situations can assist planners and managers of emergency situations.

The implementation of panic behavior in computer models is also tested by Wang (Want et al., 2015). The most important finding of this model, that fits our research, is that, when an obstacle is located on the exit route, the overall performance of evacuation (with panic behavior implementation) was worsened, in contrast to the ones without the panic factor. This difference disappeared when the exits were clear. The main reason for this result is when the panic factor is included the evacuees are instructed to gather and rush to an exit. The combination of these two factors leads to congestion when the space is limited.

Li&Han (Li & Han, 2015) introduces an interesting variance. Cellular automata (the subjects are moving using cells in a grip) based simulator allows the calibration of human behavior parameters to extract the most realistic reactions and results.

Proposing an innovative approach, Joo et al (Joo et al., 2013) present an agent and perception-based simulation program. The agents make decisions based on the perceived affordance given by the environment that surrounds them. This simulation interprets human actions as a set of perceivable action opportunities providing a model of human reactions based on the changes in their environment.

A simpler conditional approach is proposed by Bo et al (Bo et al., 2007). The rules that control the behavior of agents implement Basic Behaviors which are triggered when certain situations are applied. The Behaviors are divided into Individual and Social, but the approach is typical and is restricted to the implementation of queuing, herding and congestion.

An interesting approach is a Serious Game, which is presented by Ribeiro et al (Ribeiro et al., 2012, June). This simulator uses a 3D environment, developed using a Game Engine, and allows the participation of a single player who plays the role of an evacuee. The purpose of this simulator is the train occupants using serious games on fire drills in gaming environments but also introduces human participation in evacuation simulations. Although the purpose of this simulator is to train occupants, this approach can be a basis for further research on the impact of real human behavior during evacuation simulations. A similar approach on ships is the VELOS project, which although its primary purpose is to support ship designers in the design stage and trainers for crew training, may also be used for evacuation simulations, ergonomics, and comfortability experiments. It also supports the participation of the human users during evacuation or normal conditions that may roam the interior of the ship.

Based on the assumption that human behavior and the evacuation factors can be modeled mathematically. On top of that, human behavior and evacuation factors are of crucial importance for the simulation of evacuation. It is concluded that the Evacuation Factors set the conditions of an evacuation, whilst Human Behavior determines the outcome of the evacuation, by countering these Factors. Moreover, the previous experience from existing Evacuation Simulations shows that Human Behavior has already been implemented, by usually developing an algorithm that aspires to mimic Human Behavior. Additionally, most of the evacuations have been included in the simulator review in the previous chapter and some of them have used the models of the current chapter.

Therefore, after assessing various Human Behavior and Movement Models, it is concluded that both elements have been effectively modeled and implemented into evacuation simulators. The core part of these models is usually Human Behavior, subsequently, the implementation of an algorithm that controls the computer-controlled evacuees should be one of the most crucial elements of an ES. As we have seen and discussed above, this is not enough, as it removes the human factor from the simulation. The next step is the introduction of human players, with the simultaneous implementation of human and computer-controlled evacuees, who will be described in more detail later. The purpose of this work is the effective development of an Evacuation Serious Game/Simulator for Passenger Ships. At this point, the question is what should be included and how, to such a simulator. In the next chapter, the most crucial elements of a Ship Evacuation Simulator are reviewed and discussed, towards the development of such an application and mainly if such an application could train the passenger to behave according to the safety rules if an urgent evacuation happens.

3.8 Summary

This chapter discusses the scientific field of Human Behavior under stressful conditions and how human beings contribute, form, react or participate in evacuation-related phenomena such as congestion, bottlenecks, fire source, leader-following, etc. Most recent studies conclude that human beings will not act irrationally when in danger, while panic occurs under extreme and rare circumstances. All the elements present in an evacuation can be measured and eventually implemented in evacuation simulators.

PART III - DEVELOPMENT ENVIRONMENT

Chapter 4

4.1 Evacuation Simulator on Ships Development Guidelines

In this chapter, the basic principles that any Three-dimensional Evacuation Serious Game/Simulator should or may include, are introduced. After studying the human behavior and the evacuation factors, reviewing the elements that contribute to a reliable simulator and after extensively testing the Ship Evacuation Simulator (more details are provided to the next chapter) we should set the rules for the development of a reliable Evacuation Simulator (Ding, 2015) and based on the research by Kougioumtzoglou et al, (Kougioumtzoglou et al., 2021), specifically for the development of Ship Evacuation Simulators. The Verification and the features to be incorporated into an Evacuation Simulator are according to the IMO guidelines and its tests as proposed by Ronchi et al (Ronchi et al.,2013). This chapter studies the elements that should compose an Evacuation Simulator specialized in Ships.

4.2 Serious Game/Evacuation Simulator Use

The development of evacuation models and computer-based Evacuation Serious Games and Simulators arose from the inadequacy of evacuation drills because of their high cost, their poor repetitive capability, and their ease to cause accidents (Ren et al., 2006). Although the evacuation drills may provide us with useful information, they lack some basic elements. The most notable omissions are the psychological impact on a human being, under stressful conditions, the social forces between the evacuees, the influence of panic reactions by other evacuees, and finally the unexpected incidents that may happen during an emergency evacuation (Vorst, 2010). Moreover, the fire alarm systems (fire is the most common evacuation cause) have often failed to work "as planned" when a real fire breaks up because they were put in place with false expectations regarding how occupants behave during fires (Proulx, 2001, May). Therefore, the simulation of human behavior throughout a computer program is a challenging task.

To this end, the game-based evacuation Serious Games and Simulators are introduced as applications that aim to simulate evacuations using an artificial environment, based on realistic conditions and representing the emergency egress from an area or a structure. An Evacuation Simulation can be conducted as many times as it needs to and under every possible condition (Kuligowski et al., 2005).

The main distinction between computer-based evacuation simulators is their users' perspective. Two-dimensional simulators use dots or artifacts for the representation of the evacuees or any other elements such as fire and smoke and the viewer's perspective is usually a top-down one. A 2D approach is not inferior to a 3D one, but its usability is restricted to specific functions and specifications. The evacuation models are functionally implemented, while the evacuees are rendered symbolically, while the simulation can be accelerated or decelerated according to the user's settings. On the other hand, a 2D simulator cannot support the direct participation of a player impersonating an evacuee and therefore their unexpected behavior. The computer-controlled bots do not always act like human beings rendering the collected data less reliable (Helbing et al., 2002).

Improved and well-designed algorithms may control the bots to behave realistically but can only simulate a small portion of the qualities and the unpredictable behavior of a human being or a group of human beings. Three-dimensional simulators usually use 3D human models for the evacuees or any other roles (rescue team staff and crew members etc.). The structures (e.g., buildings) are usually 3D models of existing structures further enhancing the realism. The importance of this approach is based on the easiness and improvement of the understanding of human behavior in evacuation conditions, as the subjects are monitored while they are playing the game and some performance measures are logged to be further analyzed later on (Ribeiro et al., 2013). Nygren (Nygren, 2007) proposes that a 3D evacuation simulator can combine the focus on the behavior of individuals and the behavior of crowds, as it allows the participation of real players simultaneously with computer-controlled bots.

The following subchapters present a guide based on previous works about 3D Evacuation Serious Games and Simulators. The guidelines incorporate the most important elements from existing SG and Simulators, studies on human behavior, and studies on the theory of crowd movement. Additionally, gaming characteristics are also reviewed for studying the capabilities of game engines for the development of evacuation simulators.

4.3 Evacuation Simulators Models

For developing a Serious Game or a Simulator, the steps stated by Maria (Maria, 1997) and mentioned in Chapter 2, were followed. Evacuation Simulators Models simulate the movement and behavior of crowds. Kuligowski (Kuligowski et al., 2005) proposes a categorization of evacuation simulators, and in the perspective of SG, into three main types: Behavioral-based, Movement-based, and Partial-Behavioral. These three categories imply the most prominently applied element of each model. A Behavioral model is focused on the simulation of evacuee's behavior while a Movement on the simulation of evacuee's movement. Partial-Behavioral models are primarily Movement-based but Behavioral elements are implemented during the evacuation sessions.

Behavioral models are categorized further into No Behavior, Implicit Behavior, Conditional (or Rule), Artificial Intelligence (AI), and Probabilistic Models. The main Movement Models are the Density Correlation, the User's choice, the Inter-person Distance, the Potential, the Emptiness of the next grid cell, the Conditional, the Functional analogy, the Other model link, the Acquiring Knowledge, the Unimpeded Flow, and the Cellular automata (Kuligowski et al., 2005). Summarizing, (Ribeiro et a.l, 2013). ascertains, that the most used models are:

Cellular Automata Models: these models represent the floor as a cell grid. The occupants move from cell to cell by a simulated throw of weighted dice.

Forces-based Models; these models apply the behavior of natural forces such as Magnetic Forces, Fluid Spreading, or Social Forces, onto evacuees' movement.

Artificial Intelligence-based Models; these models attempt to simulate real human behavior, based on AI algorithms.

The implementation of the human behavior to the computer-controlled bots is considered of high importance as most of the evacuees' crowd will be constituted by these bots, which should react realistically, to provide us with valid results and help the human users to be immersed to the virtual environment.

Based on the previous knowledge and developing an actual Evacuation Simulator, the below sections present the most used elements on evacuation models and describe how their implementation affects the simulation process.

4.4 Hazardous Elements

The developers of an evacuation simulator should consider implementing elements, such as fire or smoke, which, as we have described earlier are some of the most common evacuation factors and are considered responsible for most of the injuries and the fatalities during evacuations.

4.4.1 Fire

A Fire is one of the most common evacuation causes. Thus, an evacuation simulator should include fire as one of the hazardous elements and more specifically as an element that (i) spawns fire sources of various sizes and various intensities and (ii) controls their expansion in random or specific locations. The human skin is vulnerable to heat and flame and depending on the exposure, the skin, the muscles, the respiratory system, and in extreme cases even internal organs can be affected. Prolonged exposure increases the level of burns from Level 1 to Level 5. (Lehnhardt et al., 2005, Herndon & Spies, 2001). Moreover, the flames should inflict initial and repetitive damage on humans and/or bots, simulating the burns that a real fire source may inflict. If the exposure is prolonged, the subject should be killed. The fire sources should emit heat gradually raising the temperature of the structure and subsequently harming the people inside the structure. Prolonged exposure to this heat may also cause severe damage or even death to human beings (Nastos & Matzarakis, 2012).

Apart from the damage, intense and large flames may create an impenetrable barrier that restricts the movement of the evacuees. An area covered with flames is impassable and the trespassers should be subject to serious burns if they attempt to cross it. The implementation of the fire not only affects the emotional and behavioral characteristics of an evacuee but also affects his/her physical constitution (Ding et al., 2015). An interesting inclusion would be the Fatigue factor, which will measure how tired an evacuee is. Low Fatigue, due to the high temperatures or other factors, may result to reduced speed

4.4.2 Smoke

The outbreak of a fire is usually accompanied by smoke. If a Simulator includes the presence of fire, it should also include the presence of smoke. Attention should be paid to (i) match fire and smoke, (ii) of the smoke, while it is filling the rooms and the corridors restricting the movement and vision of the occupants, and (iii) the harmful consequences of smoke inhalation. The inhalation of smoke (Lestari et al., 2006) may poison the victim with symptoms that vary from dizziness to death. Any evacuee’s vision inside a smoke-filled room should be obstructed, and their eyes may blush and hurt, reducing the importance of vision and prioritizing senses such as hearing and touching (Ronchi et al., 2018). A smoke-filled corridor or room also reduces the victims’ speed and in case of heavy smoke, the victim’s visibility is hampered (Fridolf et al., 2015). The effects may be temporary and long-term (Barregard et al., 2006). When Smoke is implemented its temperature should be increased when the fire sources’ intensity is increased and reduced when the area-to-fill is larger (Lou et al., 2017).

4.4.3 Poisonous/Toxic Gases

Poisonous/Toxic gases have been responsible for massive casualties in monumental disasters such as the one in Bhopal in 1984 (Broughton, 2005) and the one at the Northeast Sichuan Gas Field in Gaoqiao Town of Kaixian County, Chongqing, China in 2003 (Jianfeng et al., 2009), as they spread quickly and may be odorless and colorless. It has been proposed that areas filled with Poisonous gases should be accessed by remotely controlled robots (Kim et al., 2009), as they are considered extremely dangerous even for professional firefighters. The main difference between poisonous gas and smoke is that the gas is usually not associated with fire, but sometimes fire and poisonous gases provoke each other in a "domino" effect (Dou et al.. 2019). Gas might be due to a tank leak, or a heating system and its effects may vary depending on its chemical composition. We can also consider smoke as a poisonous gas but, we should consider a few factors; a gas (i) is usually colorless and odorless, (ii) tends to fill rooms and corridors very quickly, (iii) may be harmful to those who inhale it. The inhalation of poisonous gases (even for a short period) may poison the victim with symptoms that vary from dizziness to death. Gas is usually invisible, and the victims become often aware of its presence after its inhalation. In an Evacuation Simulator, the implementation should be depicted with a visual signal that indicates a lack of air and an asphyxiating feeling of the victim. As every gas has its own qualities, spread time, and impact, the influence on the evacuees should be a rapid loss of health and an increased fatigue rate.

4.4.4 Falling Objects

One of the most important advantages of computerized evacuation serious games and simulators is their safety. Falling objects during an evacuation scenario should have not been an option, as they could be potentially dangerous for the participants (Feng et al., 2018). In computerized simulators, an unlimited number of objects can be added and applied with physics. Objects should be taken into consideration, because incidents, such as an earthquake or the list of a ship may move or eject them, toward the evacuees. Especially falling objects such as rocks may result in severe injuries even if the blow is not direct and may cause damage if it lands within 5 meters of a person (Leemo & Schimelpfenig, 2003). The implementation of this feature is crucial, in the aspect of visual and practical. The simulations should be able to realistically depict the evacuation area and falling objects are commonly found in evacuation areas. The damage to evacuees should be calculated by an equation taking into consideration the speed and the weight of the object at the time of the impact.

4.4.5 Spatial Elements

The evacuated areas include various Spatial Elements such as stairs, elevators, etc. that may alter the speed and the motion of the crowds and/or the individuals. These elements are not hazardous per se but their outcome could potentially be extremely lethal. These elements should be implemented in the majority of the evacuated areas affecting the pedestrian movement.

4.4.6 Bottlenecks

As Tanimoto states (Tanimoto et al., 2010), a bottleneck situation occurs, when many pedestrians rush toward an evacuation exit causing a drastic breakdown of outflow flux from this exit owing to the human jam effect, sometimes referred to as the human arch effect. A Bottleneck denominates a limited area of reduced capacity or increased demand. For pedestrians, movement bottlenecks are usually formed by direct capacity reduction (door or corridor). Bottlenecks are of fundamental importance in the calculation of evacuation times and other observables for buildings (Kretz et al., 2006). A bottleneck and queuing effect could appear near doors or narrow corridors, when many evacuee's content pass through the narrow space stacking in front of or near the exit site, reducing their moving speed and the overall speed of the crowd. Moreover, this may result in injuries due to the concentration of such large numbers in such limited spaces. Bottleneck areas are crucial, as they affect (i) the evacuation time, (ii) the moving speed and the locomotion of the human crowds, and (iii) the behavior of the evacuees inside and the evacuees in the immediate proximity of the crowd.

During many of the evacuation scenarios on the Ship Evacuation Simulator, we were observing the congestion of evacuees inside a narrow corridor or a stairwell. Wang et al (Wang et al., 2015) describe this phenomenon as Congestion: "In the normal evacuation process, all the agents only need to arrive at the exit as soon as possible and there is no overtaking. In the congestion evacuation process, some agents want to move to the exit quickly by crowding other agents". Since under intense stress people try to move faster than normal, the overtaking and casualty phenomenon usually arises. The congestion phenomenon is very common in emergencies. The phenomena that may be observed in a congestion area evacuation is listed below:

- The spontaneous gathering of pedestrians in front of an exit.
- The formation of crowds of arched or semicircular shapes close to the exit.
- When the pedestrians find that the evacuation of the target exit is slower than other exits, they may switch their target exit.
- The pedestrians with strong physical abilities can take action by their own expectations, while those with weak physical abilities might be overtaken by stronger ones
- The casualty may occur due to asphyxiation and stampeding in times of congested areas, filled with panicked crowds.

4.4.7 Congestion Areas

During most of the simulation of evacuation scenarios on SES, evacuees have been observed to be congested into narrow corridors or stairwells. Wang et al (Wang et al, 2015) describe this phenomenon as Congestion: "In normal evacuation process, all the agents only need to arrive at the exit as soon as possible and there is no overtaking. In the congestion evacuation process, some agents attempt to move toward the exit quicker than the other by crowding other agents. Some interesting ideas can be extracted by studies on traffic congestion such as reduced speed if there are no backup or alternative evacuation routes (Zhang et al, 2019; Tanaka et al, 2007). Since people under stress try to move faster than normal, the overtaking and casualty phenomenon usually arises. Areas with high congestion density reduce the evacuees' speed more than slightly congested areas (Chu et al, 2017; Zhang et al, 2020). The congestion phenomenon is very common in emergencies and can cause the following effects:

- A spontaneous gathering of pedestrians in front of an exit.
- Formation of crowds of arched or semicircular shapes close to the exit.
- When the pedestrians find that the evacuation of the target exit is slower than other exits, they may switch their target exit.
- The pedestrians with strong physical abilities can take action by their own expectations, while those with weak physical abilities might be overtaken by stronger ones.

- The casualty may occur due to asphyxiation and stimulation in times of congested areas, filled with panicked crowds.

During an evacuation scenario, the evacuees should be applied with a Congestion Penalty (P_C), when passing through a congested area. The speed reduction should be proportional to the congestion density.

4.4.8 Counterflow

After a disaster, a number of people tend to move against the mainstream of evacuees toward their cabins or seats in order to search for their relatives and gather their belongings or their life jackets. This flow of passengers is called Opposite-Flow or Counter-Flow significantly reducing the overall moving speed, because of the resulting overcrowding and counterflow (Yoshida et al, 2001). It has been observed that during a fire, even the firefighters might create an Opposite-Flow phenomenon, while they move towards the fire source and the evacuees attempt to move away from it (Łozowicka, 2010). Counterflow may completely break the movement of a crowd by blocking it if its strength is significant (Li et al, 2019). Another type of Counterflow is called Merging and is created when two opposing flows of evacuees meet up on a staircase when both flows are merged and their movement is negated (Heliövaara et al, 2012). In an evacuation simulator, any member of a flow that encounters a counterflow should be a subject of reduced speed.

4.4.9 Stairs

Walking on staircases is a complicated three-dimensional movement and its modeling is a challenging task. Several studies are focused on the effect of the crowd or individual's movement on stairs and stairwells and the use of elevators during an evacuation. Norén (Norén et al, 2014), Hoskins (Hoskins et al, 2012), and Qu et al (Qu et al, 2014) state particular issues that should be taken into consideration and applied to evacuation simulators.The physical exhaustion of the evacuees, particularly when they ascent the stairs. An exhaustion penalty should be applied to the evacuees' fatigue, ascending a stair after taking the below factor into account:

- The stairway height, the slope effect, the depth of the tread, the height of the riser, and the presence and the location of the handrails affect the evacuation speed. As an example, a tall stairway requires an increased workload in comparison to a shorter one.
- Short staircases may temporarily increase the speed of specific types of evacuees.
- The bottleneck effect is barely found on stairs.

4.4.10 Elevators

One of the most common beliefs is that during an evacuation an elevator's shaft should be avoided, due to the danger of entrapment. In contrast, recent studies have shown that an evacuation assisted by elevators has many advantages. Some of them are the vertical opposed to smoke's motion movement of the elevators, the easiness for the elderly (as they do not have to climb stairs), children and physically impaired (they can be easily stampeded in stairs or narrow corridors), the familiarity of the people because of their daily use and the minimum physical effort that their use demands

(Kuligowski, 2003). The disadvantages are the poor reliability, the piston effect that can induce fire spread, the difficulties on evacuation organization, especially when a crowd of people attempts to enter the limited space of an elevator (Chen et al., 2016; Ding et al., 2015). Elevators should be an interesting and valuable addition in evacuation simulators, in proper simulated areas such as skyscrapers, ships, metro stations, etc.

4.5 Human and Crowd Behavior

Human evacuation demands the implementation of human behavior in Evacuation Serious Game and Simulators. These characteristics aim to realistically predict human behavior during an egress. There are three main approaches for evacuation simulation models: macroscopic, mesoscopic, and microscopic. The macroscopic considers the evacuees while the microscopic handles each evacuee, as an individual. The mesoscopic approach combines the macroscopic and microscopic approaches. Although a microscopic approach is computationally expensive, it provides more reliable results than a macroscopic approach, as each individual acts according to the behavior of a single person (Lee et al., 2003). The movement and behavior of a crowd of evacuees may harm members of the crowd and/or other evacuees or may lead to disastrous incidents. Analyzing studies on hypothetical scenarios (Vorst, 2010), real evacuations (Fahy & Proulx, 1997), and evacuations drills (Zhao et al., 2009), it is suggested that the simulation of a crowd or individual evacuees should follow basic phases. Additionally, other behaviors such as follow-up and mimic should be integrated into the evacuees' behavior and are also listed in the upcoming subchapters.

4.5.1 Basic Phases

Pre-movement or initial response time phase:

1. Recognizable signs forecast a disaster.
2. Initial Awareness of the Incident.
3. Perception of Seriousness.
4. Gathering of personal belongings.
5. Alerting other people/discussion with other people.

Movement phase:

1. Beginning of immediate evacuation based on specific behaviors:
    - Overactive, non-effective behavior, out of emotional control (15%).
    - Apathetic and nervous behavior, lack of initiative (75%).
    - Calm, with the overall picture, vigor, and potential leadership (10%).
2. Searching/Gathering of family/friendly persons.
3. Location recognition.
4. Follow or lead a group.
5. Some help other evacuees/Firefighting (a portion of the evacuees).
6. Move toward an exit.
7. Search for an alternative exit if others are blocked.

Rescue Phase:

- Survivors are in general safe.
- Evacuation is sometimes acute, because of injuries and physical damage.
- Survivors are ready to evacuate or to be evacuated

4.5.2 Behavior Under Panic/Herding Behavior/ Stressful Conditions

A stressful condition may cause panic reactions. Panicked evacuees sometimes transfer the control to others but contrary to the Leader-following behavior (which is described in subchapter 6.4), this behavior is irrational and leads to harmful decisions such as ignoring the side doors and eventually to an increase of the overall fatalities. Helbing et al (Helbing et al., 2002, p.6) list several reactions of panicked evacuees (the elements of this list should be randomly microscopically and macroscopically implemented on an Evacuation Simulator as it is proposed in brackets):

1. In escape situations, panicked individuals get nervous, i.e. they tend to develop blind actionism (Microscopic).
2. People try to move considerably faster than normal (Microscopic).
3. Individuals start pushing, and interactions among people become physically unnatural (Microscopic).
4. Moving and passing a bottleneck frequently becomes uncoordinated (Macroscopic).
5. At exits, jams build up. Sometimes, arching and clogging are observed (Macroscopic).
6. The physical interactions in jammed crowds add up and can cause dangerous pressures up to 4,500 Newtons per meter, which can bend steel barriers or tear down brick walls (Macroscopic)
7. Escape is slowed down by fallen or injured people turning into obstacles (Microscopic).
8. People tend to show herding behavior, i.e., to do what other people do (Microscopic and Macroscopic).
9. Alternative exits are often overlooked or not efficiently used in escape situations (Microscopic).

4.5.3 Fatigue

As Vøllestad states (Vøllestad, 1997) states that "Muscle Fatigue has been defined as an exercise-induced reduction in the maximal capacity to generate force or power output". Fatigue should be applied to the evacuees/avatar as they are standing (low increment), walking, running, swimming, or climbing stairs (high increment). Additional factors that contribute to increased Fatigue could also be Smoke and Extensive Heat. Stress alone is considered a contributing factor, but it could be implemented as a factor of low impact (Gaillard, 2001). In general, healthy and young adults are more tolerant to Fatigue than older or persons with health issues (Enoka & Duchateau, 2016). Therefore, a numerical or progress bar display of the evacuees' fatigue levels, coupled with some impact to the avatar's condition (reduced speed, blurred vision, etc.) could help the human users to better understand their condition.

4.5.4 Mimic Behavior and Initial Response

People are usually mimicking the reactions of their neighbors more than the reactions of distant people. The influence between two people is reversely proportional to their distance. People tend to continuously observe the reactions of others and mimic their reactions. At the initial phase of an evacuation the reactions of other people affect the reaction of everyone who can see them and inaction by some people can affect the observers, who as a result may ignore the danger (Nilsson & Johansson, 2009).

4.5.5 Leader Following Behavior

People, usually, tend to follow leaders during a disaster. A leader could be a stranger, a relative, or a friendly person that takes this role after the outbreak of a disaster. Alternatively, a leader could be a crew member, a rescue team member, or the staff of a store. The followers usually accompany one or more leaders, composing groups of evacuees, towards an exit or a safe place. Trained leaders (e.g. crew members) contribute significantly to the evacuation process. Even a small number of trained leaders may increase the number of successfully evacuated people. We can see a significant difference even if only 25% of the total leaders are trained (Pelechano & Badler, 2006). On the other hand, a high number of leaders may create a chaotic situation, because of the conflicting behavior of multiple leaders (Ji & Gao, 2006). A Leader-Following Behavior should be implemented on an Evacuation Simulator microscopically measuring, on the one hand, the scale of social status, the influence, the prestige of the Leader and on the other (i) the familiarity between the leader and every follower, (ii) the alleged family relationship and (iii) the age and the social status of the followers.

4.5.6 Children

A special group of evacuees is the children, especially from 2 to 7 years old. Children evacuation cannot be described with models for adults, as their size is smaller, and they are slower (Lárusdóttir, 2014). Children are motivated by different incentives relative to adults. As Kholshevnikov et al mention "A characteristic feature of children's behavior (especially of preschool children) is acting without thinking, under the influence of momentarily occurring feelings and wishes. These wishes and feelings are first caused by an intermediate environment, and things catching its eye". The childrens' pre-movement time (time before their initial movement after the outbreak of the disaster) is longer compared to an adult because they tend to stay in place even after a vocal sign waiting for their educators (many experiments are conducted at schools) to take them by the hand (this should be implemented to an evacuation simulator). Therefore, the immediate intervention of adults is critical for the evacuation of children, because of their tendency to remain in the same place or to search for their parents or teachers in random locations. The pace of children is slower than an adult one because of the small size of their feet but it can be increased using handrails and if they are holding their hands. Moreover, children have a significantly increased pre-movement time (Kholshevnikov et al., 2009; Kholshchevnikov et al., 2012). In contrast, they are less likely subjects of the congestion effect because of their small size.

4.5.7 Physically Impaired People

Physically Impaired people compose a separate type of evacuee. They are divided into two main categories; the ones who can move on their own and the ones who are unable to. Disabled people in a wheelchair can move on their own but they cannot use stairwells (the use of a motion platform is an alternative for stairwells, if available) and their speed is generally slower compared to the other evacuees (Miyazaki et al., 2004). During an evacuation, a wheelchair occupies the space of 2 or 3 occupants, when placed into a corridor (Żydek et al., 2021). Physically Impaired people who cannot move on their own, ought to be carried by others (relatives, staff, or random individuals).

Auditory-impaired evacuees respond to visual warning signs (voices announcements, alarms), while visually impaired evacuees respond to auditory signals (flashing signs) (Proulx, 2002; Renne, 2006).

4.6 Special Elements

The elements in a Simulated area are not always harmful nor the scenery of an evacuation simulator is always a building. Evacuations may occur in ships, airplanes, oil platforms, underground metro, and train stations, and in every natural or artificial human-inhabited area. The proposed special elements are listed in upcoming subchapters.

4.6.1 Ship Evacuation

After analyzing the data from previously conducted simulations, with our ship simulator, and research studies in relevant fields (Yoshida et al., 2001; Schreckenberg et al., 2001; Łozowicka, 2011; Valanto, 2006), the conclusion that a ship demands a specialized approach on serious game/evacuation research, because of its unique evacuation environment, has been reached. The characteristics, that should be taken into consideration in a ship evacuation simulation are (i) the list of a ship under natural forces such as the inlet of water, the shift of the cargo, a strong storm, a collision with other ships, or large objects (the probable rotation cases are Listing, Rolling and Pitching in both directions) (ii) the motion of a ship by ship's engines or by the waves, (iii) the varieties of types of ships (High-Speed Passenger Ships, Ro-Ro, Cruise Ships), (iv) the difficulty to escape from a ship because of the large body of water around it, (v) the presence of crew members who usually contribute positively during an evacuation (the degree of contribution is defined by their training level), (vi) the high number of families and children. Vassalos et al give a new definition which is called Evacuability and is defined as “The ability to evacuate a ship environment within a given time and for given initial conditions" and an equation (Vassalos et al., 2004, p.2-3) in order to calculate it:

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

where:

E = Evacuability

env = Ship's model

d = Initial Conditions

r(t) = Response Time

$s(n_i)$ = Walking Speed of individual flow units

The most important special characteristic of a ship evacuation are listed below:

- **Ship's List:** We suppose that a ship's heel is 0 degrees under normal circumstances. We concluded that when a ship banks, the consequences are the following:
  - Unstable and angled floor that disrupts normal movement and forbids running.
  - The objects slide toward the direction of the ship's wheel.
  - On high degrees of heeling the doors and windows become impassable as they are placed at high altitudes due to the rotation of the ship.
  - The need for evacuation is imminent because the complete immersion of the ship may be immediate.

- **Water Inlet:** The inlet of water into a ship is the prelude to a forthcoming sinking. The inlet may happen by (i) a crack at the lower decks, by a collision such as the Titanic (Howells,1999, p.23, 30-33), (ii) a hardware failure (abruption of the front door), such as at the Estonia disaster (Jasionowski & Vassalos, 2011), (iii) high listing degree. The effects of water inlet is (i) progressive flooding of the ship's compartments, (ii) progressive sinking of the ship, (iii) panic reactions by the evacuees to whom the compartment is being flooded, (iv) drowning of a number of evacuees. The effects of water on the evacuees are referenced later in this book.

4.6.2 Water

The Cold, Frozen or Hot water may affect human health and in case of submersion, the individual begins to drown. When humans are washed by frozen or cool water no physical damage is caused (Barcroft et al., 1943). In contrast, a long stay inside a cold-water volume gradually causes damage to the victim's health and leads him/her to faint and die (Choukroun et al., 1989). On the other hand, hot water may result in severe burns.. The total immersion in a water volume results in the suffocation of the victim and after a period he/she faints and dies (Layon & Modell, 2009).

4.6.3 Other Fluid Spread

The spread of fluid might solely cause a disaster or might coexist with the main cause of the evacuation. The fluid may be harmless or extremely harmful. A harmless non-toxic fluid such as an antifreeze fluid mainly disrupts the evacuation by increasing the floor's slippery and by worsening the walking ability of the evacuees. A harmful fluid, such as an acid in large quantities, could harm the evacuees. The fluid spread can be implemented using fluid spread equations such as those which Solomenko et al propose (Solomenko et al., 2015).

4.7 GAME ENGINES OVERVIEW

A well-designed Virtual Environment with improved graphics, advanced physics and proper audio effects might immerse the users in a virtual world, temporarily distracting their senses from the real world and focusing their thoughts and attention in the artificial environment. Once this happens users' reactions get closer to reactions during a real accident (Louka & Balducelli, 2001). An Evacuation Simulator which allows the participation of users via virtual avatars should immerse the users into the virtual world so that they could act such as being in a real accident (Ribeiro et al., 2013; Mól et al., 2008). Hu (Hu et al., 2012) states that “It has been proven that the mechanics simulation based on a 3D game engine is not only available but also has lower development difficulty, more interactivity and more reusability than the traditional techniques" and that the game engines are very powerful research tools. Therefore, the Game Engines are considered as a highly valuable tool for the development of Evacuation Simulators.

The development of 3D Virtual Evacuation Simulators could be materialized with the use of Game Engines, for the design of the Virtual environment and the implementation of all the rules and features of the simulation. Game Engine started as modding engines for published first-person games such as Doom and Quake, in the mid-90s and evolved to develop games from scratch. Sometimes the difference between a game and a Game Engine is blurry, but what differentiates them is the data-driven architecture of Game Engines (Gregory, 2018).

A development alternative could be the use of OpenGL or DirectX for a top-down development of the virtual environment and its qualities, such as the simulator developed by Chiewchengchol (Chiewchengchol et al., 2011), but this approach is expected to be extended the development time, increasing the complexity, while a game engine may provide us with the needed tools without the extra effort. The most popular Game Engines so far are the Unreal Engine 4, the Unity Game Engine and the CryEngine. This type of software can be used for the creation of games, simulators and movies. The Game Engine's selection is crucial as the essential features and qualities of the Simulator are defined by this. This chapter quotes the essential features and capabilities a Game Engine must support to match the needs for the development of reliable 3D Evacuation Simulators. Every Game Engine uses its own terminology to name similar features, so we will use the most commonly used naming conventions. The information in the subchapters below is retrieved from the Unreal Engine 4 documentation webpage (https://docs.unrealengine.com/en-US/index.html), Unity Manual webpage (https://docs.unity3d.com/Manual/index.html), CryEngine documentation webpage (https://docs.cryengine.com/) and the extensive testing of the above-mentioned Game Engines, as well as from the OpenGL documentation page https://www.khronos.org/opengl/. The criteria are set based on the research on the topic and the development of the SES (Bishop et al., 1998; Anderson et al.,2008; Eberly, 2006), that proposes the criteria of Efficient display, Dynamic Collision Detection, Scene Management, Terrain and Scene, Animation and Programming Language. Therefore, extending the above, a new set of categories was created to evaluate are Portability, GUI, Accepts External Models, Physics Implementation, **Controls, Camera, Character**, AI Tools, Programming Language(s), Documentation, Complexity, Lightweight, Game Engine. The above features are listed into Table B in Appendix A and detailed herein:

- **Portability:** The application may run to multiple Operating Systems and devices.
- **GUI:** The application provides a user-friendly Graphical User Interface.
- **Accepts External Models:** Complex models should be designed to third-party applications (3DS Max, Blender etc) and imported to the Game Engine. This feature measure how feasibly the application handles external models.
- Physics Implementation: Gravity, friction and other physical properties and functions are provided by the engine.
- **Controls, Camera, Character**: The three Cs criterion measures how easily the engine sets up the Characters, the camera and the controls.

- **AI Tools:** The application supports the implementation of AI, with build-in AI functions and tools.
- **Programming Language(s):** The application supports programming and what are the supported programming languages.
- **Documentation:** How extensive is the Documentation and the How supportive is the User Community.
- **Complexity:** How complicated is the development of a virtual world in the application.
- **Lightweight:** The computational power required to operate this software.
- **Game Engine:** The application is a Game Engine or something else, such as an API.

4.7.1 OpenGL

OpenGL is generally a lightweight approach, although it is not a Game Engine, it is a State Machine and specifically an Interface in the GPU, with only a complex initial setup (OpenGL Overview, n.d.); (De Vries, n.d.)/; Kessenich, et al., 2016). Its complexity and weight is increased as more features (Colliders, Physics, etc.) and libraries ought to be added. OpenGL can only render graphics, while it needs multiple libraries to add rendering windows (GLFW), to add math functions (GLM), to add models (ASSIMP), and audio (Irrklang). OpenGL, though highly portable, does not provide a Graphical User Interface, therefore all the elements and functionality should be implemented with coding. No built-in features or tools accompany OpenGL, whereas all the functionalities should be developed from scratch. The latter could discourage most developers, as they first need to develop a Game Engine and then an evacuation simulator. If this approach is chosen, then the application may meet precisely the needs of the developers and create a high-performance application, but the extra development time and effort would be a serious drawback.

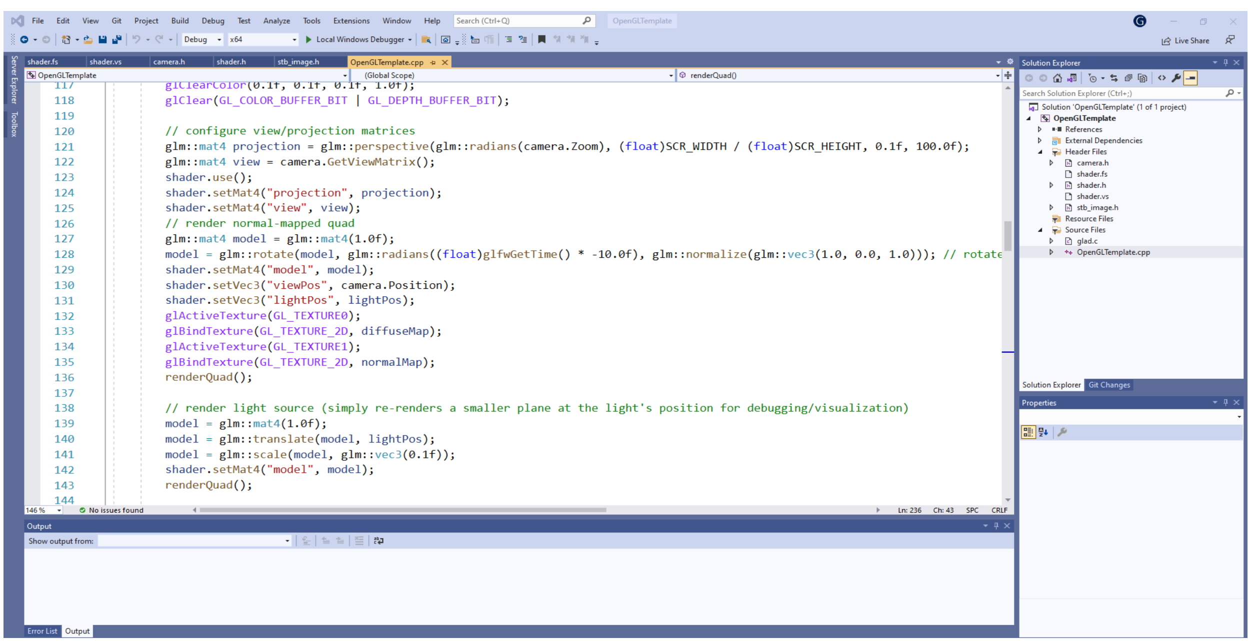


Figure 28. OpenGL Programming Interface (non-GUI)

4.7.2 Cry Engine

CryEngine is a Game Engine with a convenient real-time lighting engine, which is its major advantage, and it is considered state-of-the-art. It supports advanced terrain and animation tools Mittring, M. (2007). Therefore, CryEngine has poor documentation and the users' community is sparse and does not provide a robust architecture for implementing objects. Its shortcomings are that it uses LUA for coding (although it supports C++), which is not as popular as other programming languages, and its user interface is not user friendly (Šmíd, 2017).

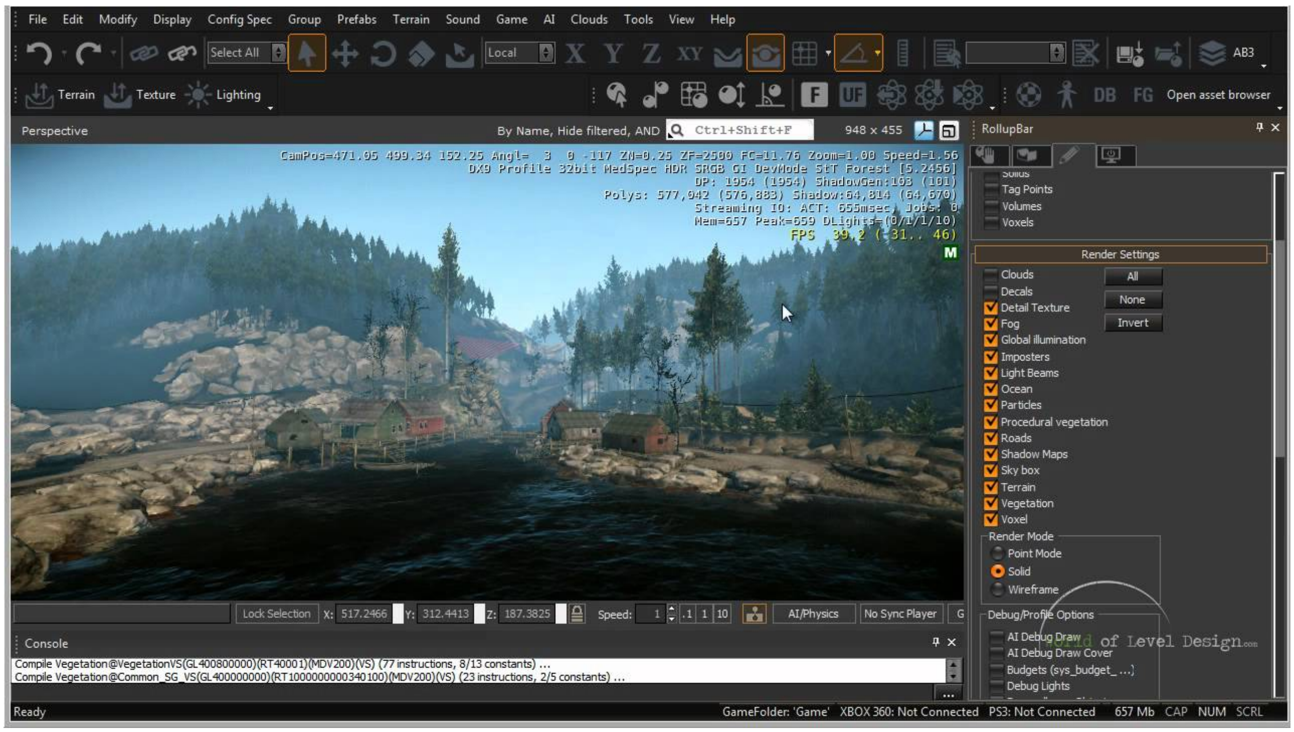


Figure 29. CryEngine Graphical Interface (retrieved from Youtube)

4.7.3 Unreal Engine 4 and Unity Game Engine 5

Currently, the best approach for the development of a 3D ES would be either Unreal Engine or Unity Game Engine (Šmíd, 2017; Dickson et al., 2017). Both Unreal (UE) and Unity (UGE) Game Engines provide the tools to implement the virtual world. They both support an Object-Oriented approach as all the objects in a map can be transformed to Blueprints (UE) or Game Objects (UGE) and are enhanced with extra features and behavior, such as movement. Both Game Engines may easily handle complex external models and apply different types of colliders onto them. Moreover, Physics settings are provided by default and can be modified at will to match the particularities of every environment. The controls are provided, but the developers need to set them up and adjust them to the needs of the application. They both support AI systems, but Unreal Engine provides a more robust system, and specifically it is based on the system of Behavior Trees (tree-like flowcharts for Behavior), Blackboards (store important locations or persons), and special-purpose programs called

Services, Decorators, and Tasks (SDT). Behavior Trees are used for developing a tree-like structure (see Figure 29) of actions a bot may take. Blackboards are attached to the Behavior tree, storing locations, entities, and characters, and work as the memory storage of a brain. Finally, Services, Decorators, and Tasks are attached to behavior trees, updating, and enhancing them with any newly collected information. All the decisions are based on the conditions set to behavior trees through sequences of SDTs.

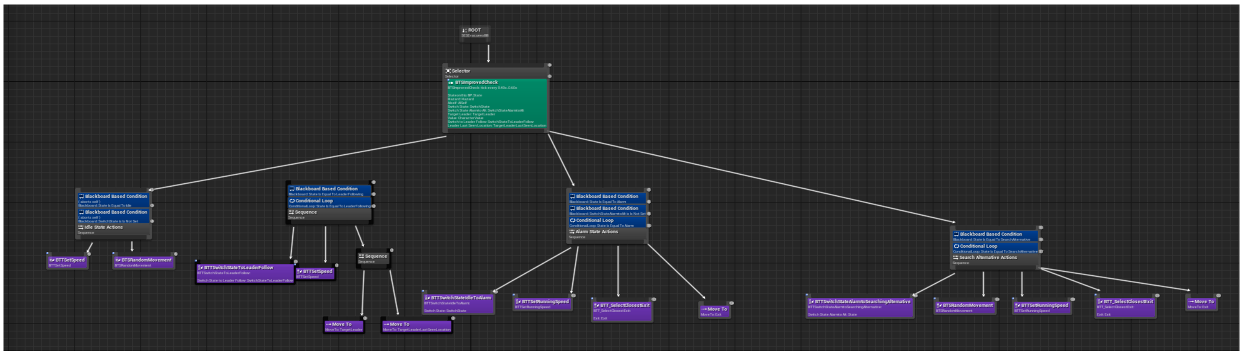


Figure 30. Unreal Engine 4 Behavior Tree in SES

The other main difference between the two candidate Engines is the development of the code. Unity uses C# or Boo scripting, in separate files, that can be attached to Game Objects applying their functionalities to them. On the other hand, Unreal Engine uses C++, while it provides a graphical development interface named Blueprint Scripting Blueprints are programming classes and function similarly to C++ classes, with Inheritance, Polymorphism, Encapsulation, and even Abstract classes. The code could not be in separate files, but it is part of every object - Blueprint. UE4 and Unity 5 effectively handle the external model, as most of them are imported without distortions, keeping their features and animation properties. The networking and multiplayer are implemented through scripting and both engines are fully capable of creating highly scalable and reliable multiplayer online games, with a high number of participants.

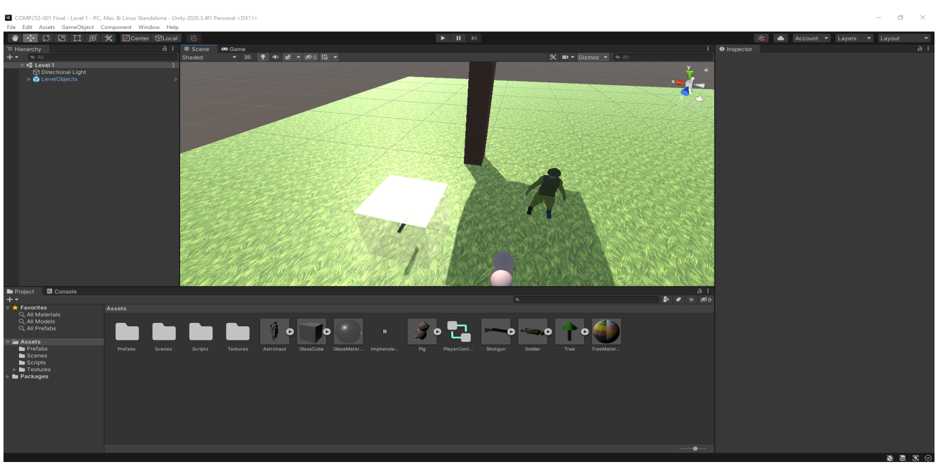


Figure 31. Unity Game Engine Graphical Interface

Subsequently, Unreal Engine 4 has been selected as the best contemporary option for the development of 3D ESs. It provides a simple interface, with easy model import, without any issues, and AI tools, capable of creating fast, lightweight applications. Moreover, UE4 is supported and updated with new versions and patched from Epic Games and it is assisted by a large community of developers. Unreal Engine is multiplatform and can create applications for many operating systems and devices. The only thing that the developers need to do, would be to pack the final version of the application into a different format.

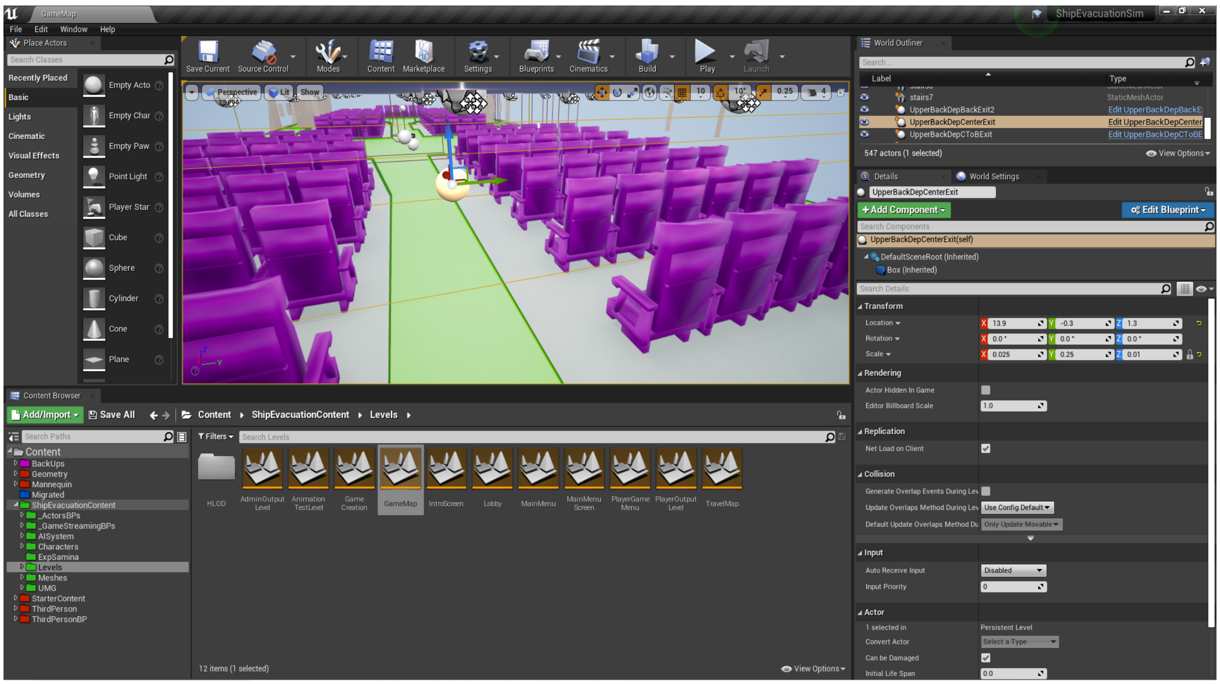


Figure 32. Unity Game Engine Graphical Interface

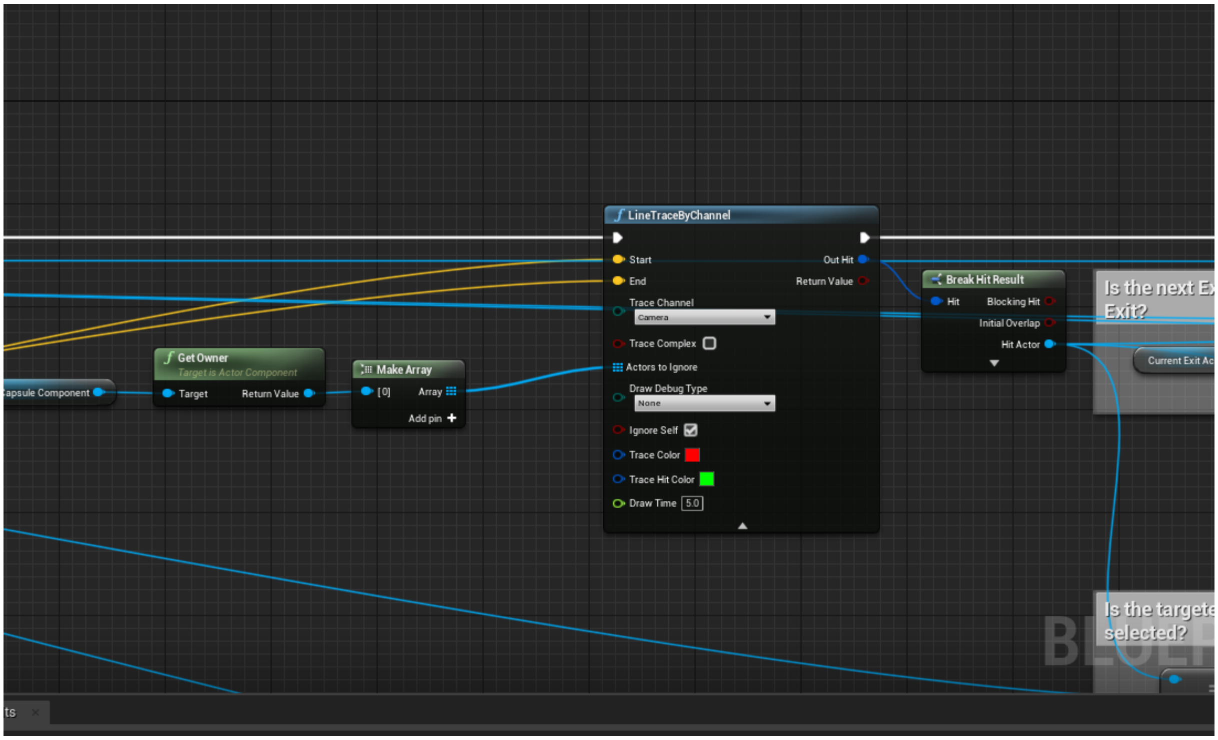


Figure 33. Unreal Engine Scripting Language (Blueprints)

4.8 Virtual World Development

Apart from the main simulated area all simulations require to be part of a wider environment to represent a realistic environment. The sky, the ground, the static items such as the buildings and the trees, the water volumes, the lighting (lighting will be discussed in separate subchapter) are developed with the Game Engine's built-in tools. Some of these elements can also be developed by 3D Graphic Rendering Software but the implementation in the Game Engine's built-in tools simplifies the development process.

4.8.1 Flexibility on model importation

There are two main categories of 3D models: Skeletal and Mesh. A Skeletal model is a creature with a bone structure and the ability to walk, move and perform various tasks. On the other hand, meshes are items such as chairs and desks, structures such as buildings and cars, and every non-living asset of the virtual world in general. The designers create the 3D models with 3D Graphics and Rendering Software (3D Studio Max, Blender, etc.) but a Game Engine may import specific types of models. The most common 3D model file types are Collada (.dae), FBX (.fbx), 3DS Max file (.3DS), Blender files (.Blend) and Wavefront files (.OBJ). A developer transforms models from type to type using the appropriate 3D Graphics software; 3D Studio Max or Blender for FBX.

From the model importation perspective, a Game Engine should be:

- **Effective;** the model, its textures, and any other components should be imported and easily incorporated into the engine.
- **Fast;** the importation should be completed fast (depending on the model's LOD and size), because of the high computational power needed for rendering and simulating the virtual world.
- **Simple;** a complex importation procedure may end up consuming the system's resources or discourage the developers from importing complicated models.
- **Adaptable**; a Game Engine needs to handle different 3D models' types and recognize the difference between a Skeletal and a Mesh Model.

Although all Game Engines use different options, some elements should be prioritized, when importing new models such as (i) their collision properties, (ii) their animation properties, (iii) the models' quality properties, (iv) the skeletal - mesh discrimination options, (v) the texture and materials options, (vi) the transformations.

4.8.2 Multiplayer

A standalone simulation assigns the role of evacuees to AI-controlled bots, as human players do not directly participate. A single-player simulator allows the participation of a single player (as evacuee) and the control of other evacuees is assigned to AI-controlled bots. A useful addition to an Evacuation Simulation should be the Multiplayer option, as most Game Engines support this type of game architecture (Normoyle et al., 2012). If the developers of a Simulator are interested in enhancing their software with Multiplayer, this addition will provide reliable data such as (i) the results human-players of the behavior, (ii) the measurement of the scale of immersion, (iii) the motion and the actions of single evacuees or of crowds of evacuees (consisted of real humans) can be recorded or observed and can be applied to AI-bots' movement in order to increase the reliability of the locomotion of AI-controlled bots. Another application would be the assignment of rescue team members, crew members or staff members to real players for training purposes (Sharma et al., 2015, June; Sharma, et al., 2019).

4.8.3 Administrator - Player Architecture

A crucial architectural setup should support two modes: Administrative mode and Player mode. An Administrator should (i) create and set up the options of the simulation sessions, (ii) spawn events during a session, (iii) observe and assess the overall procedure, (iv) assure the normal execution of every session, (v) collect and store the output of the evacuation sessions. On the other hand, a player should participate in several evacuation sessions (created by an administrator) following the instructions and notes to assure the validity of the result of his involvement. This setup is common in popular multiplayer games such as World of Warcraft and Elder Scrolls Online, as well as in Simulators such as SAFEgress (Chu et al., 2014), Velos (Ginnis et al., 2010), and EPES (Quagliarini et al., 2014) and crossbreeds such as BudBurst Mobile (Han et al., 2011, October).

4.8.4 AI Implementation

The Evacuation Simulators usually assign the control of the evacuees (bots) to the AI (except for the simulators that support real users). The Game Engines usually contain a built-in AI control system, as described by Xi (Xi et al., 2015, January). Some of them are based on behavior trees and others on programming the behavior of the bots. Every bot should be enhanced with some instructions that control its behavior and implement a decision-making mechanism. As an example, the selection of the escape route/exit or the evasion of a fire source is implemented by the AI system. The AI algorithm that will guide a bot into a fire toward a door won't realistically simulate human behavior. A useful feature is the crowd management systems that some Engines provide. These systems allow the definition of AI-controlled crowds to simulate the locomotion of huge groups of evacuees (apart from the AI implementation on every evacuee).

4.8.5 Physics

With Physics, we mean the law that governs how large objects move under the influence of gravity and other forces and have been present since the first games were developed (Millington, 2007). Therefore, Millington (Millington, 2010) states "when we talk about physics in a game, we really mean game mechanics, that is, the laws that govern how large objects move under the influence of gravity and other forces". When an object such as a ball is pushed, it will probably roll on the floor and after a period of time, it will stop moving, under the effect of rubbing. Another example is a feather falling from above, towards the earth; it will fall to the ground after a period attracted by gravity. All the objects and the living creatures inside a virtual environment must on any occasion obey the laws of physics. If some assets of a virtual world do not fully obey the laws of physics the application ceases to be a Simulator and it is drifting closer to a regular game. A Game Engine should implement and modify Physics on every object or creature. The most important features to be implemented on every object or creature are listed and analyzed below:

- **Gravity;** Every movable object or creature is subject to gravity. The developers must set the gravitational options that match every object. As an example, a heavy object usually falls faster than a lighter one. The weight of an object can be modified by handling the mass options that are described in the Mass subchapter.

- **Movement**; All objects inside a virtual environment can be set to Static or to Movable. The developers must set as static objects anything which is difficult or impossible to be moved, such as a bolted table, a house, or a statue. These objects are not allowed to be moved by any means and are computationally less demanding. Every object that can be moved must be set as Movable. Movable objects react after the application of a force on them and are moved accordingly, cumulating their mass and their rubbing scale. A Movable object is computationally costly due to its ability to actively interact with other objects and forces.

- **Rubbing;** The movement of a moving object that encounters another object is affected by the scale of rubbing. The rubbing is affected by the texture and the material of the object. Attention must be paid to the scale of rubbing since a high rubbing scale should cause the objects to hardly move, while a low rubbing scale should cause them to slide and move even after the slightest application of force.

- **Determination of mass;** A feature that can be met in a Game Engine is the capability to adjust the mass of an object. An indicative mass value is assigned to every object which is created or imported in the virtual environment. The mass of the object is analogous to its material. An iron ball of the same size as a rubber ball weighs more and the mass must be set higher.

4.8.6 Collisions

Even if the objects and the creatures in a simulation act according to the laws of physics, it is very important to be able to interact with other objects. The effect of the contact of two or more objects or creatures is called Collision and is partially related to Physics. As an example, if two spherical objects collide, then both objects (i) need to verify the collision, (ii) both objects should respond to the impact considering their material. speed and the direction of the collision. The speed and the direction (a vector) are used to calculate the objects' behavior after the collision, such as their bouncing, their destruction, etc. Some of the Collider types are listed below:

- **Shape-based Colliders:** The Game Engines provide built-in types of colliders based on shapes such as Cylinder, Sphere, Box that create an invisible barrier around an object or a creature. To avoid excessively expanded colliders, the developers have to limit the radius of the colliders (Unreal Engine Documentation, Unity Documentation). AABB-AABB-based Colliders are the most common and easily implemented (Policarpo & Conci. 2001).
- **Modifiable Colliders:** An alternative collision method, which is not based on shapes, is provided by most Game Engines as a Modified Collision method. The designer sets the quality of the collider, and the software creates a new and attached object or creature collider enhancing their natural interaction with other objects. On the other hand, this method requires the consumption of higher computational power because of the high level of detail of the colliders to match the exact shape of every object.

- **Graphic Modeling Software Applied Colliders:** A third option is the use of 3D Graphics Modeling Software such as 3D Studio Max, Maya, or Blender (a freeware program), for the creation and application of collision to objects and creatures. This approach is described in detail in the 3D Graphics Modeling and Rendering Software chapter.

Unnatural Colliders

A widely applied collider around an object or a creature forbids other objects or creatures to effectively interact with it, creating an invisible and impenetrable barrier. On the other hand, the absence of Collision may result in irrational and unnatural events such as objects that pass-through walls. In contrast, a falsely applied collider may transform an element of gas or liquid form to a solid object, e.g., a volume of water cannot be covered by a solid and impenetrable collider. In the case of evacuation simulators, the colliders Shaped-based Colliders, with specific dimensions are proposed, as they work reliably and are easily applied. Another advantage of the Shaped-based colliders is that they effectively allow the implementation of congested areas and bottlenecks when the size of the evacuees should be calculated and compared to the dimensions of the area.

4.8.7 Lighting

The Light Sources are built-in features of Game Engines, but they can also be created in 3D Modelling Software (Blender, 3D Studio Max, etc). Light types have their own qualities and are used on different occasions. The most common and critical adjustments are the light's intensity and color. A lamp or the sun inside a virtual world won't emit any light because of its nature as a graphic model. The only way to emit light is to attach them to a light source. A virtual world without the addition of a Lightmap (an organized collection of light sources) is totally dark. Although the main types of lights can vary according to the developing Engine, they are more or less similar and are referred to below.

- **Spotlight:** A Spot Light emits light from a single point in a cone shape in which the light falls off. The radius of light defines the length of the cone. It is usually used for flashlights, car headlights, and searchlights.

- **Point Light:** A Point Light is located at a point in space and sends light out in all directions. The intensity diminishes with distance from the light, reaching zero at a specified range and the light is equally emitted in all directions. Point Lights work as real-world light bulbs.

- **Directional Light:** A Directional Light simulates light that is being emitted from any identifiable source position. All objects in the scene are illuminated as if the light is always from the same direction. All shadows cast by a directional light will be parallel, making this the ideal choice for simulating sunlight.

- **Sky Light:** A Sky Light captures the distant parts of your level and applies that to the scene as a light. That means the sky's appearance and its lighting / reflections will match, even if your sky comes from the atmosphere, or layered clouds on top of a skybox (a virtual box or sphere which represents the sky in a virtual environment), or distant mountains.

- **Area Light/Rectangular Light:** An Area Light/Rectangular Light is defined by a rectangle in space. Light is emitted in all directions, but only from one side of the rectangle. The light falls off over a specified range.

4.8.8 Materials and Textures

The selection of the Material and Texture of objects is crucial for the realism of the simulator. A Game Engine should include the Physical Material application option. A proper Physical Material application enhances the realistic locomotion of objects and creatures, as it defines the physical abilities of an object. A rubber ball should bounce on a wall but an iron one should fall against the floor. Materials can be imported or created in Rendering Software.

4.8.9 Programming Languages

The design of a virtual environment is the visualization part of an evacuation simulator. The other part is the ability of the Game Engine to program the various elements of the virtual world. The movement of an object, the switch of lights, or the properties of a mesh are subjects of programming. Game Engines use three ways to add programming capabilities; existing programming languages, integrated on the Engine programming languages, and visual scripting.

- An existing programming language (such as C++, C#, or Javascript) with the addition of game engine's libraries can handle the programming of a simulation properly. The pros of this approach are the possibility of prior knowledge of this language features by the developers and the integrity and portability a popular programming language provides. The cons are the probable complicated and unfamiliar library keywords and their unclear implementation inside the programming code, which requires a long time of familiarization by the programmers.

- Programming languages (such as Boo on Unity) are developed in order to function on the engine. The positive aspect is the high integration degree in the Game Engine's structure and the negative one is the poor portability of the programming code.

- Another approach is the use of Visual Programming (such as the Blueprints in UE4). The algorithms are developed using pre-created blocks of instructions and their proper connection functions as a programming language. The pros of this approach is the ease and the simplicity of the code development, accessible even to developers with poor programming knowledge. The cons are the poor portability of the code and the fact that most programmers are not accustomed to this development method.

4.8.10 Menu and HUD Creation

Although the implementation of menus is not a core component for an evacuation simulator, it increases the software's usability and realism. On the other hand, a HUD (Heads-Up Display) provides the user with an in-game menu that informs him of his avatar's health condition, position, or other information and provides the administrator with tools for setting up and managing evacuation sessions. The most important elements to include in a HUD are listed below:

- User:
  - Health: A numerical or visual indicator about the avatar’s health.
  - Fatigue or Stamina: A numerical or visual indicator about the avatar’s Fatigue levels or Stamina.
  - Breathing Indicator: A graphical indicator that displays the avatar’s breathing pace and in the case of lack of oxygen, this should be indicated by a change in color and/or flashing.
- Admin:
  - Spawning Menu: All the elements should be listed in such a menu. When the admin selects one element, it should be spawned into the simulated area after clicking on it.
  - Lights Menu: Controls the lights of the area.

- Day/Night: A menu to set Day or Night conditions.
- Spatial Phenomena Indicator: Indicates phenomena such as Bottlenecks or Congestions.

4.8.11 Data Reference

Elements such as the total evacuation time, the casualties' number, the door selection, etc. should be stored for further reference. The most important elements are listed in the Evacuation Analysis chapter of this article. Additionally, nonnumerical data such as the bottleneck recognition should be inspected by the administrators or the spectators of a simulation. This feature should be provided to administrators by the developers by (i) allowing them to inspect the area of evacuation, without physically interacting with it, (ii) allowing the inspection by changing the perspective to top, bottom, left, right view, (iii) indicating the spatial phenomena (Congestions, Bottlenecks) applying a color when such an event is recognized by the software, (iv) recording the evacuation session.

4.9 3D Graphics and Rendering Software

Selecting suitable 3D Graphics and Rendering Software is crucial for the development of a virtual simulation. The most popular 3D Graphics applications are 3D Studio Max, Maya, and Blender, which are fully capable of modeling the assets that compose evacuation areas. The models should be created by 3D Rendering software. The main requirements a 3D graphics software should meet are listed below:

- **Object Rendering**: At first, every object in the evacuated area should be designed and modeled. The proper design refers to the correct shape, dimensions, and physical qualities of the virtual object. For example, a wooden drawer should be similar in shape and color (the color of wood), its shelves should be moved if a force pulls them out. Additionally, the dimensions of a real drawer should be applied, and the proper weight and mass should be set. The Rendering software provides the users with measurement tools that allow them to create objects with the correct proportions. Even if some objects are too large or too small, the Game Engines allow the scaling of objects.

Elements	Description
Evacuee's Crowd Composition	The numerical and percentage representation of the individual categories of evacuees. We propose the display of (i) Men - Women, (ii) Adults - Children - Elders, (iii) Disabled - Non-Disabled, (iv) Passengers - Crew - Staff - Rescue Team Members.

Total Evacuation Time	The total evacuation time from the spawning of the initial events till the evacuation of all the evacuees or the termination of the evacuation egress.
Total Percentage and Numerical output of Safely Evacuated	Output formatted such as 75% and 323/1500 where the first number indicates the safely evacuated persons and the second the total initial number of evacuees.
Percentage and number of deceased divided by cause of death	The percentage and number of deceased persons divided by cause of death. E.g. Fire 55% and 55/100 where the first number indicates the first number indicated the deaths due to fire and the second the total number of deceased evacuees.
Percentage and number of injured divided by injury cause	The percentage and number of injured persons divided by cause. E.g., Fire 70% and 70/100 where the first number indicates the injured evacuees by fire and the second the total number of injured evacuees.
Percentage and number of deceased divided by category	The percentage and numerical display of deceased evacuees are divided according to the victim's category. E.g., Children 25% and 25/100 where the first number indicates the deceased children by fire and the second the total number of deceased children.
Percentage and number of injured divided by category	The percentage and numerical display of injured evacuees are divided according to the victim's category. E.g., Children 32% and 32/100 where the first number indicates the children injured by

	fire and the second the total number of injured children.
Exit selection	The percentage and numerical display of evacuees because of their exit selection and category. E.g., Side Door A: Total 10% and 10/100. Men 30% and 3/10 - Women 70% and 7/10.
Other measurements	Some structural elements such as the influence of stairs ascension or a smoke-filled corridor can be measured separately.

Table 16. Evacuation Elements Output

- **Application of Colliders:** The creation of a virtual object does not determine its actual boundaries. If the object is imported into a game engine without the application of a Collider, a collision with other objects won't result in a collision. A collider is the invisible surface of an object which forces other objects to interact with it. As an example, if a human model attempts to step toward a wall without the application of a collider it will pass through the wall; if a collider is applied on the wall then the human will hit the wall. A key feature for the integrity and realism of a simulation is the application of a collider on all objects. Alternatively, colliders can also be applied by Game Engines, which is one of the easiest approaches, as the colliders can easily be modified in the Engine.
- **Pivot Point application definition:** We call Pivot Point the spot that is virtually the center of an object and is indicated as the starting point (usually a dot) of three axes (usually X, Y, Z). This is the point that defines the axis or the base of its movement and rotation and it should normally be set near the center of the object.
- **Materials application capability:** An object without the application of a material is usually colored by a single default color. The material is a combination of colors, shades, filters, and pictures that are applied on the surface of objects in order to improve their realism.
- **Animation application:** The creation of human models is accompanied by the application of animation as the models should be able to move according to real humans. This is a challenging procedure and demands a good knowledge of 3D Graphics software.

- **Exportation Format:** The created models are exported as files of a certain format. Attention must be paid to the compatibility of the exported file format and the acceptable game engine format.

4.10 Simulators, Serious Games, and Gaming Characteristics

A well-designed virtual environment with improved graphics and proper sound effects can immerse the users in a virtual world, temporarily distracting their senses from the real world and focusing their thoughts and attention in the artificial environment. A game-based evacuation simulator that allows the participation of users via virtual avatars should immerse the users into the virtual world so that they could act such as being in a real accident.

The development of 3D virtual SG and evacuation simulators requires the use of game engines for the design of the virtual environment. The most popular game engines so far are Unreal Engine 4, the Unity Game Engine, and CryEngine. The Game Engine's selection is crucial as the essential features and qualities of the Simulator are defined by this. Apart from the main simulated area, all simulations require to be part of a broader environment to represent a realistic environment. The sky, the ground, the static items such as the buildings and the trees, the water volumes, the lighting are developed with the game engine's built-in tools. Some of these elements can also be developed by 3D graphic rendering software but the implementation in the game engine's built-in tools simplifies the development process.

Moreover, a standalone simulation assigns the role of evacuees to AI-controlled bots, as human players do not directly participate. A single-player simulator allows the participation of a single player (as evacuee) and the control of other evacuees is assigned to AI-controlled bots. A useful addition to an evacuation simulation should be the multiplayer option, as most game engines support this type of game architecture. If the developers of a simulator are interested in enhancing their software with multiplayer, this addition will provide reliable data such as (i) the results human-players of the behavior, (ii) the measurement of the scale of immersion, (iii) the motion and the actions of single evacuees or of crowds of evacuees (consisted of real humans) can be recorded or observed and be applied on AI-bots movement in order to increase the reliability of the locomotion of AI-controlled bots. Another application would be the assignment of rescue team members, crew members, or staff members to real players for training purposes.

Furthermore, a crucial architecture setup is the support of two modes: Administrative mode and Player mode. An Administrator should (i) create and set up the options of simulation sessions, (ii) spawn events during a session, (iii) observe and assess the overall procedure, (iv) assure the normal execution of every session, (v) collect and store the output of the evacuation sessions. On the other hand, a player should participate in several evacuation sessions (created by an administrator) following the instructions and notes to assure the validity of the result of his involvement.

In addition, the evacuation simulators usually assign the control of the evacuees (bots) to the AI (except for the simulator that supports the participation of real players). The game engines usually contain a built-in AI control system. Some of them are based on behavior trees and others on programming. Every evacuee should be enhanced with some instructions that control his behavior and implement a decision-making mechanism. E.g., The selection of the escape door or the avoidance of a flame is implemented on bots by the AI system. The AI algorithm of a bot that mindlessly runs through a flame toward a door is not properly developed. A useful feature is the crowd management systems that some engines provide. These systems allow the definition of AI-controlled crowds to simulate the locomotion of huge groups of evacuees (apart from the AI implementation on every evacuee).

When an object such as a ball, is pushed by a force (or the hand of a human), will possibly roll on the floor and after a period, it will stop moving, under the effect of rubbing. Another example is a feather falling from above, towards the earth; it must fall to the ground after a period due to the effect of gravity. All the objects and the living creatures inside a virtual environment must on any occasion react according to the physical laws. If some assets of a virtual world do not fully obey the laws of physics the application ceases to be a simulator and is shifted to a regular game. A game engine should implement and modify the parameters of physics on every object or creature. The most critical features to be implemented on every object or creature are presented in Table 3.

Even if the objects and the creatures in a simulation act according to the laws of physics, it is very important to be able to interact with other objects. The effect of the contact of two or more objects or creatures is called collision and is partially related to Physics. When two balls collide together both balls must be aware of the collision and should respond to the impact considering their applied material and the speed of collision. A widely applied collider around an object or a creature forbids other objects or creatures to approach it, creating an invisible and impenetrable barrier. On the other hand, the absence of Collision may result in irrational and unnatural events such as objects that pass-through walls. In contrast, a falsely applied collider may transform an element of gas or liquid form to a solid object, e.g. a volume of water cannot be covered by a solid and impenetrable collider. Light types have their own qualities and are used on different occasions.

Moreover, the selection of the material and textures of objects is crucial for the realism of the simulator. A game engine should include the physical material application option. A proper physical material application enhances the realistic locomotion of objects and creatures, as it defines the physical abilities of an object. A rubber ball should bounce on a wall but an iron one should fall against the floor. Designing a virtual environment refers to the designing part of an evacuation simulator. However, the ability of a game engine to program various elements of the virtual world refers to programming characteristics. Game engines use three ways to add programming capabilities; existing programming languages, integrated on the engine programming languages, and visual scripting.

Although the creation of menus is not crucial for the evacuation simulation itself it increases the software's usability. On the other hand, a HUD (Heads-Up Display) provides the user with an in-game menu that informs him of his avatar's health condition, position, or other information. Elements such as the total evacuation time, the casualties' number, the door selection, etc. should be stored for further reference. The most important elements are listed in the Evacuation Analysis chapter of this article. Additionally, non-numerical data such as the bottleneck recognition should be inspected by the administrators or the spectators of a simulation. This capability should be provided to administrators by the developers by (i) allowing them to inspect the area of evacuation in a ghostly form, (ii) allowing the inspection by changing the perspective to top, bottom, left, right view, (iii) indicating the problematic areas applying a color when such an event is recognized by the software, (iv) recording the evacuation session.

Another crucial element for the development of a virtual simulation is the 3D graphics and rendering software (e.g., Studio Max, Maya, Blender). The main requirements that such a 3D graphics software should meet are Object Creation; Colliders application; Pivot Point application; Materials application capability; Animation application capability and Exportation Format.

Finally, to demonstrate, assess, and evaluate the results of a virtual evacuation session we propose the measurement and observation of the elements.

4.11 Summary

After assessing various existing Evacuation Serious Game and Simulators and developing a prototype (SES), some rules and features critical for every Evacuation Simulator have been selected. The first step is the selection of the proper framework for the development of such software and the Game Engine was proposed as the most suitable option. A Game Engine already has features such as Physics, Colliders, Model Handling. Programming Interface and AI system in a compact package, saving time and making the development simpler. After the selection of the Game Engine, the features that should be implemented as reviewed and assessed, such as the Fire, Smoke, Toxic Gases, Evacuee Types, etc., are also proposed.

PART IV – SHIP EVACUATION SIMULATOR & CONCLUSIONS

Chapter 5

5.1 Ship Evacuation Simulator

Modern ships have become larger in scale and function, and their complexity has been increased considerably. This brings up many difficulties in evacuation and rescue when an emergency occurs. Therefore, effective evacuation and risk methods should be predicted and applied to design safety training and education. Therefore, a Three-Dimensional Ship Evacuation Serious Game (SES), has been developed facilitating the impersonation of evacuees by computer-controlled autonomous bots (agents) that perform a risk assessment and continuously calculate route conditions, communicate with neighboring occupants, determine bottleneck points, and select the best evacuation routes. The simultaneous participation of human users and computer-controlled bots as evacuees in gamified multiplayer scenarios by the runtime spawning of 3D elements such as fire and smoke is introduced. SES is a game-engine-based simulator with several benefits such as flexible technology and economic feasibility. Realistic and valid results can be obtained by applying SES in evacuation simulation.

5.2 Introduction

The cruise travel market is experiencing rapid growth worldwide (Wang et al., 2019). In addition, due to several maritime disasters, passenger ship evacuation in case of emergency has received increasing attention recently (Stefanidis et al., 2019). It is essential to gain insight into factors such as the evacuation time. The evacuation of large passenger ships such as cruises is one of the most complex processes, since there are numerous people in the interior of an isolated, moving structure, over an unsafe medium, such as the seawater volume (Wang et al., 2014). Those factors transform the evacuation of a passenger ship, to a unique and individual evacuation subject, completely distinct and with numerous differences, compared to the evacuation of buildings or other structures and vehicles (Guarin et al., 2004). Disasters to other means of transportation or structures have relatively lower casualties, compared to the ones in ships (Harrison, 1989).

Ship designers must run several tests to check all the amendments and create the concept of a “safe return to port” (Vassalos et al., 2010). To do so they can run an evacuation drill which is a planned evacuation scenario, with predefined rules and conditions, involving several volunteers, impersonating the evacuees. While evacuation drills may provide useful information and data, they are impractical and costly to run (Couasnon et al., 2019). The development of evacuation models and computer-based evacuation simulators arose from the inadequacy of evacuation drills because of their high cost, their poor repetitive capability, and their ease to cause accidents (Ren et al., 2006). Although an evacuation drill may provide useful information it lacks some basic elements. Drills, by their nature, cannot include and consider some significant factors such as the psychological pressure due to the stressful and hazardous conditions of an evacuation and moreover the social forces between the evacuees (e.g. parent-child relation, leader-following, herding) (Bryan, 1999). The panic reactions of the evacuees, the unexpected incidents that can happen during an emergency evacuation, and the changes in the spatial characteristics of a ship’s structure can completely alter the output of an evacuation drill (Vorst, 2010; Wang et al., 2016). On top of that, the fire alarm systems (fire is the most common evacuation cause) have often failed to work "as planned" when a real fire breaks up because they were put in place with false expectations regarding how occupants behave during fires (Proulx, 2001).

Some of the above-mentioned factors can only be included in computerized evacuation simulators, where computer-controlled escapees evacuate a structure under specific rules and factors. Previous research uses simulations to track passengers during an emergency (Couasnon et al., 2019; Hu et al., 2019). But, while such applications can incorporate several features, such as the hazardous elements, the spatial characteristics, and the evacuees' movement, they do not simulate human reactions based on psychological pressure. Therefore, there is a need for works that show how realistically the conditions of an emergency ship evacuation can be simulated by an application that can effectively collect output data of realistic evacuation scenarios (Nevalainen, Ahola, & Kujala, 2015). Furthermore, previous works do not usually consider the three-dimensional (3D) perspective but in contrast rely on two-dimensional environments (Ha et al., 2012). Moreover, works that combine artificial intelligence (AI) with human users could alter the way we see evacuation scenarios (Kim et al., 2004). Finally, most ship simulation environments are either too complex or oversimplified, and only a few are freely distributed for community usage (Couasnon et al., 2019).

To annul these inconsistencies, this work proposes a game engine-based Ship Evacuation Simulator called SES. The basic idea of this work is to develop a 3D multiplayer simulator specialized in passenger-ship evacuation. In addition to that, we evaluate how capable SES is to reliably simulate evacuation scenarios, which involve large numbers of evacuees, hazardous elements, and ship motion. The main motivation lies in the need to collect big amounts of data from ship evacuation simulations for future HCI research and two of the most iconic accidents involving passenger ships in Greece, the Express Samina, and Superfast III, with significant loss of life (Niininen & Gatsou, 2008; Goulielmos et al., 2009; Papanikolaou et al., 2004). Both accidents had 14 and 80 casualties, respectively and alarmed the authorities about the sea travel safety in Greece, especially during the summer months, where a great number of tourists choose this type of transportation.

The SES environment is about a passenger ship and includes all the elements that may exist in a passenger ship, such as listing, fire, fog, etc (Kougioumtzoglou et al., 2021). The main idea behind SES is i. the improvement of the reliability of the simulation and ii. the motivation of human users to act realistically, while they are immersed in the 3D virtual environment. Elements such as fire or smoke are simulated and represented as 3D entities. Predefined scenarios are created and executed, while there is the option to spawn events or elements in runtime. Human players coupled with computer-controlled bots participate as evacuees, attempting to escape the structure, pursuing clear goals and being rewarded for their success, adding the necessary gamification elements, and improving realism. The results of every scenario are collected and can be reviewed and assessed further. Human behavior under panic and during critical situations is implemented based on the assumptions by Keating (Keating, 1982), Quarantelli (Quarantelli, 2001), and Santos (Santos & Aguirre, 2004). These studies state that in contrast to the older beliefs, people in dangerous situations won't panic and won't be acting irrationally, as the popular culture has established. Instead, most people rationally, make logical decisions and tend to help others, whilst they attempt to save their lives and the lives of their family, friends, and/or associates (Ribeiro et al., 2012).

Therefore, this paper studies how realistically the conditions of an emergency ship evacuation can be stimulated by such an application and how capable it is to collect the output data of evacuation scenarios. Finally, this work considers whether AI-controlled bots can act such as a human player should have acted, and to what degree and how runtime events (fire, fog, etc.) could alter the course of an evacuation scenario.

5.3 Existing Work of Evacuation Simulators

Based on Law and Kelton (2000), a simulator is a computer software used to evaluate a model numerically and the gathered data is used in order to estimate the desired true characteristics of the model. As a result, the simulator imitates the operations of real-world facilities or processes and models the assumptions about the function of a system, based on mathematical or logical relationships. To this end, an evacuation simulator is a computer program that is assigned to imitate the process of evacuation incidents and produce results similar to the ones that a real-world evacuation would provide. Evacuation simulators are categorized by their basic features and capabilities and are focused on replicating various aspects of an evacuation incident. There are simulators modeling crowd movement, agent behavior, the spread of fire or smoke, etc. Previous simulation programs focus on various areas like:

- Single Rooms.
- One floor buildings.
- Multilevel buildings.
- Skyscrapers/High-Rise Buildings.
- Airports.
- Airplanes.
- Campuses.
- Hotels/Resorts.
- Underground facilities (metro stations, train stations, underground tunnels, and shopping areas).
- Sea Vessels.

The evacuation of a ship is a subject of extensive research since the beginning of the 20th century (Shiwakoti et al., 2009), due to the resulting high casualty rates, its multifactorial and complex nature. Passenger ships can accommodate several thousands of people and for any review rule, it is crucial to define inspection objectives according to different stakeholders that are involved in the shipbuilding process (Amirafshari et al., 2018). For example, the aim of a shipowner is to ensure that the system is made as good as possible, with minimum maintenance costs. Shipowners have the ships classed under classification societies that inspect them. Classification societies are NGOs that establish and maintain technical standards for shipbuilding and operation. Ship designers, on the other hand, may feel that some rules are overly conventional and do not consider the welding quality achieved. This means that they are required to do the same extent of inspection as a manufacturer with a reputation for less emphasis on the welding quality. A ship evacuation simulator can support these stakeholders and help ship designers to evaluate (early in the design process) passenger activities on a ship for different conditions of operations and to improve the design accordingly (Ginnis et al., 2015).

There are also essential regulations that are followed in ship construction and evacuation scenarios. The International Maritime Organization (IMO) has introduced a series of guidelines for undertaking complete evacuation analysis and certification of large passenger ships within the design stage. There is also SOLAS, an international treaty that establishes minimum safety requirements for merchant shipbuilding, facilities, and service. Another important aspect for sea vessels is the jurisdiction under whose laws the vessel is registered (Flag State) and the jurisdiction under the laws of the visiting port (Port State). While the Flag state jurisdiction is mandatory, the Port State jurisdiction is optional (Molenaar, 2007). A simulator can be used by the Port and Flag State authorities to verify if the ship holds the safety standards set by IMO or ILO (International Labor Organization), reducing the probability of refusal to the right of entry, based on safety issues.

Crowd simulation has always been a hot topic in computer graphics, cognitive science, and AI, which combines mechanics, sociology, psychology, and operations research, and other disciplines. However, it is difficult to model human perception and decision-making (Boulougouris & Papanikolaou, 2002). Simulating crowds in the virtual environment generated by a computer can provide great help to emergency responders and thus performs an important function in reducing the damage. The next subsections present the most common features of evacuation simulators

5.4 Characteristics of evacuation simulators

Evacuation simulator models simulate the movement and behavior of crowds. Kuligowski, Peacock, and Hoskins (2005) propose a categorization of evacuation simulators into three main types: Behavioral-based, Movement-based, and Partial-Behavioral. These three categories imply the most prominently applied element of each model. A Behavioral model is focused on the simulation of evacuee's behavior while a Movement on the simulation of evacuee's movement. Partial-Behavioral models are primarily Movement-based but Behavioral elements are implemented during the evacuation sessions. Behavioral models are categorized further into No Behavior, Implicit Behavior, Conditional (or Rule), Artificial Intelligence (AI), and Probabilistic Models. The main Movement Models are the Density Correlation, the User's choice, the Inter-person Distance, the Potential, the Emptiness of the next grid cell, the Conditional, the Functional analogy, the other model link, the Acquiring Knowledge, the Unimpeded Flow, and the Cellular automata (Kuligowski et al., 2005).

Each evacuation software implements movement capabilities for the agents and some of them enhance them with a certain degree of behavior. Kuligowski (Kuligowski et al., 2005) divided evacuation models into three major categories: (i) behavioral, that is referred to models that implement behavior on the agents' movement, (ii) movement, that do not include behavioral aspect on the agents' movement and (iii) partial-behavioral, that combine the other two categories.

Moreover, there are several Evacuation Models, based on the implementation method of the agent's behavior within a simulator. In the "no behavior" Model, the agents could move but no behavior is implemented on them. There is also the Model of "rule-based behavior", which is implemented by (i) enhancing the agents with personal characteristics that affect their reaction and movement, (ii) introducing incidents, environmental conditions, and (iii) allowing the correlation and interaction between the agents. When a condition is triggered, the agents react accordingly. There is also the Model of "probabilistic behavior" where many rule-based models are stochastic and the results are calculated by the continuous repetition of certain simulation sessions, which produce various outputs. Finally, there is the "Artificial Intelligence" Model, in which the behavior of the agents is simulated based on AI equations to mimic the reactions of real humans during evacuation events.

In most simulators, agents are initially set to specific unimpeded velocities and any changes are applied by the simulator when the agents enter congestion and queuing areas, where the agents are gathered and jammed due to the limited space and the high-density situation. The agents' movement can be also categorized, based on the agent's movement method as shown in Table 17 below.

For the development of the evacuation model, we followed the process proposed by Maria (Maria, 1997), and i. the problem was analyzed ii. formulated, iii. read data was collected, iv. the model was developed and formulated, v. the model was documented for future use.

Models	**Description**
Density Correlation	The density of the space defines the speed of a single agent or a group of agents.
User's Choice	The speed, flow, and density values are assigned by the user to certain spaces of the building.
Inter-person Distance	Each agent is surrounded by a 360° "bubble" defining a certain minimum distance between other agents, obstacles, items, and components of the building.
Potential	A grid cell in space is assigned with a number value (potential). The agents move on the cells while trying to lower their potential. The potential of the cells can be modified by the user, in order to indicate the attractiveness of an exit, the patience of the agent, or the familiarity of the agent with the area.
Conditional	Conditional Behavioral models define the movement of a single agent or a group of agents based on environmental, structural conditions, the correlation, and the interaction with other agents. The model ignores much of the effect of congestion areas.
Acquiring knowledge	Acquiring Knowledge models focus on the knowledge, where it is acquired during the evacuation. The knowledge consists of the recognition of congestions, bottlenecks, etc. There is no real movement algorithm because evacuation time is not calculated.

Unimpeded flow	Unimpeded flow models calculate the unimpeded movement of the agents while adding or subtract delays and improvement times to deduce the final evacuation time result.
Cellular automata	The agents of this model move from a cell on a grid space to another cell by the simulated throw of a weighted die.

Table 17. Evacuation Models (Kuligowski et al., 2005)

Users' immersion is one of the key features of virtual environments, such as computer games or simulators. Brown and Cairns (Brown and Cairns, 2004) argue that in the stage of the "total immersion" the user's senses are cut off from the real world and only the end of the computer game is all that matters. The level of immersion is defined by the interest that a virtual world causes to the player, the permanent existence of tasks to complete, and continuous update of challenges) and the feeling of flow, where people are completely absorbed in the activity (IJsselsteijn et al., 2007).

Most of the evacuation software simulates the evacuation of computer-controlled agents - bots, enhanced with a behavioral algorithm. The user can interact with the simulation by setting the evacuation rules (number of occupants, crowd composition, events, etc.) rules, before or during a simulation session, typically as administrators. The participation of real users as evacuees allows us to observe and assess human behavior and human crowd movement. If a portion of the whole crowd of evacuees is composed of real human players, impersonated by their avatars, the simulation sessions are affected as a procedure and as an outcome, because the human behavior may be differentiated from the agents' - bots' behavior. During an evacuation session, the elements of human behavior that can be observed are i) the behavior of the under-stressful condition, ii) initial response time and iii) the path selection. As an outcome of an evacuation simulation session, the alteration of egress time and casualties' rates due to human participation can be calculated. In addition, specific simulators can be used as a virtual training field for personnel, ship designers, or rescue team members (e.g., VELOS (Ginnis et al., 2015)).

The main advantages of the Three-Dimensional perspective are i) the participation of real players in the simulation process (either as evacuees or as Administrators), for testing and/or for training purposes, which is impossible in Two-Dimensional simulators and ii) the real-time monitoring of spatial events, such as the bottlenecks and the counterflow.

A two-dimensional perspective is used, mainly, on earlier models of simulators. As the graphics technology and computer's capabilities improve, we notice that the latest models support three-dimensional perspectives especially the ones that allow user participation in a Virtual Reality environment.

5.5 Software Architecture

The idea behind this work is to combine all the elements of an evacuation with a simulator resulting in an Evacuation Serious Game and partially an Evacuation Simulator. This distinction means that the application is a Serious Game for Passenger Training but it also holds some Simulation elements, such as the movement and behavior of the computer-controlled evacuees. The proposed simulator is named Ship Evacuation Simulator (SES) and it is developed with Unreal Engine 4, one of the most popular Game Engines of our age. The simulator is specialized on ships, but with minimal modifications can be easily used in any environment. The crucial features of the SES are Gamification, the combination of computer-controlled, human-controlled evacuees, and the implementation of some ship-related particularities, such as listing. SES supports the visualization of a complete evacuation, detects bottlenecks, and analyzes evacuation routes using a routing algorithm. For the Behavior of the Evacuees, a combination of the Affiliation and the PADM models has been implemented in the algorithm. Moreover, SES supports specific techniques for the operative description of every single involved agent.

5.5.1 Serious Game Features

The Serious Game aspects of the Ship Evacuation Simulator are shown in the following aspects:

- The didactic theme of the application, where the users are trained to safely evacuate a ship and familiarize themselves with the ship's structure.
- The gamified environment, with the tasks, goal and challenges for the students.
- The implementation of the edutainment elements, with which the users are educated on realistic evacuation conditions.
- The lighting conditions of the ship's interior.
- The outbreak of fires and the presence of smoke and poisonous gasses.
- The presence of fog.
- The day/night conditions and illumination.
- The inlet of seawater.

5.5.2 Simulation Features

The simulation aspects of the Ship Evacuation Simulator are shown in the following aspects:

- The motion of the ship and how it affects the evacuees and the objects in the interior of the ship.
- The spatial conditions in the ship's interior such as the congestion and the bottlenecks.
- The motion and the behavior of the human crowd and individual evacuees. While an evacuation session runs, a number of (or all) the above-mentioned elements are triggered or spawned, aspiring to simulate authentic evacuation conditions.

The evacuees are human-like models and are controlled either by the AI (in this case the evacuees are called bots) or by human players (are called avatars). User-players control their avatars - evacuees pursuing to survive and/or help other evacuees while evacuating the ship. Bots are capable of dynamically recognizing the optimum visible escape routes (Dynamic Routing Redirection or DRR), following the optimum routes (Optimum Route Following or ORF), following leaders, parents, or crew members, and imitating the social behavior of other evacuees (bots or avatars).

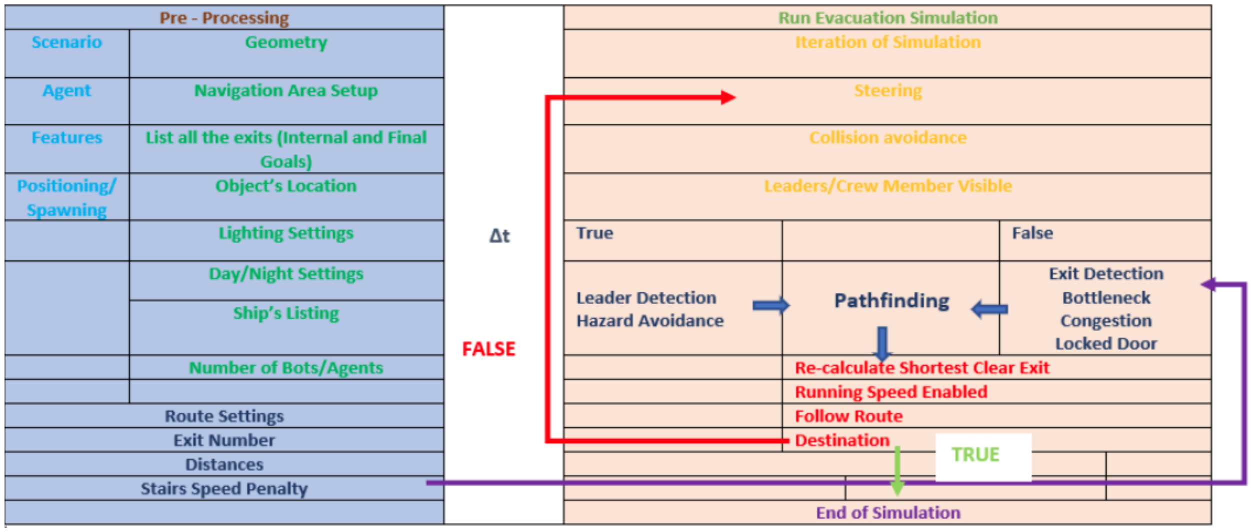


Figure 34. Process of evacuation simulation

5.5.3 Gamification and Edutainment Elements - HCCo

Deterding (Deterding et al., 2011) argues that games are characterized by explicit rules systems and the competition or strife of actors towards discrete goals or outcomes. Based on that assumption, we have implemented a gamification element to SES, to assess their impact on the simulation. The proposed simulator is gamified since it integrates game mechanics to motivate participation, engagement, and loyalty (Hamari et al., 2014) (Deterding, 2012) More specifically, it implements antagonistic elements, conditions that contribute to the immersion of the user and clear pursuable by the user and rewarding goals. Moreover, with the use of Gamification on SES, we avoid all the evacuation-related dangers that may cause severe injuries or even death in real life (Mestre et al., 2006).

SES is categorized as a Multiplayer Action-Role-Playing Serious Game (MMO-ARPSG). Multiplayer, since there are several human players, can join an evacuation session, survive, help others or just simply escape, controlling their avatars. Role-playing since the avatars come with fixed capabilities, strong and weak points based mainly on their age and sex. These capabilities may vary from the speed to the height of an avatar. This feature greatly improves the immersion level of the human players and the realism of the simulation, as the players feel that they control a real human being. The action element contributes to the holistic nature of the otherwise mindless avatars as the human users control their actions. The coexistence of Human Players and Computer Controlled Bots as evacuees is called Human-Computer Cooperation (HCCo) and is considered as one of the key elements of this simulator. Lastly, SES's gamification aspects are shown by the following factors:

- Human users are immersed in a virtual environment due to the realistic graphics, sounds, and evacuation environment.
- There are clear goals for human users to motivate them to participate in the simulations As Dubel (Dubbels, 2013) states: "by removing purpose, the player may abandon the game (or in our case the simulator) for lack of challenge", so we ensure that this won't happen during the simulation, continuously motivating and challenging the players.
- Moreover, there is a competitive environment among the human players and the bots, with a clear final goal to save their lives.

- The interactivity i. among the users and ii. among the users and the computer-controlled bots.

5.6 Game engine, Graphics, and Aesthetics

SES has been developed using up-to-date technologies from the field of video games. Unreal Engine 4 (UE4) was the development environment of SES. UE4 was proven ideal for the development of large and complicated projects such as an Evacuation Serious Game. Its simplicity and extensive documentation allow developers to contribute only a short period of time for the initial setup of the application since they can easily import graphic models from third-party software, develop algorithms and simulate physics (Mól et al., 2008). Moreover, the UE4 game engine provided all the important features and tools for the development of SES, as listed in Table 18.

UE4 game-engine features that were used in SES	Includes 3D rendering tool of textures, materials and objects.
	Provides UI design tools, suitable for the game menus and HUDs.
	Allows the implementation of the forces of nature (Physics), such as gravity, friction, and motion.
	Wraps physical boundaries (colliders) around virtual objects and characters, allowing them to physically interact with other objects or characters.
	Enhances bots with intelligence based on a built-in AI system (behavior trees and blackboards).
	Implements exterior illumination and weather condition elements such as the sun's position or the appearance of fog.
	Implements internal or artificial illumination elements in the form of various types of light sources, such as point lights and spotlights.
	Allows the broadcasting of voices, announcements, alarms and any other sounds from sources such as speakers, evacuees or objects.
	Imports models developed using third-party software such as chairs, tables and even evacuees.
	Provides the Blueprint Block Scripting Language and the C++ Programming Language.
	Provides networking tools, allowing the simultaneous participation of many human users.

Table 18. Basic game-engine features used in SES.

Objects such as chairs, tables, drawers, and doors, were designed using 3D Studio Max (Autodesk, 2020). 3DS Max was chosen since it creates qualitative, fully functional 3D objects and sets their properties (such as the pivot point, center of gravity), dimensions and surface friction) and adds colliders, setting the interaction rules between objects.

Finally, human characters (Avatars) were created with Mixamo Fuse 3D human character modeling application (Mixamo, 2020). Mixamo was selected for the quick, qualitative and easy creation of exportable human models of any kind, race, sex and age (Figure 2). These models can be easily uploaded at Mixamo's webpage and animated by picking animations from a considerable collection of animations such as running, idling, swimming, falling, or dying. The last step was to import all the models to Unreal Engine 4 and place them. All the areas were populated with fully interactive objects, based on Express Samina's blueprints and images.

Figure 34. A Group of spawned evacuees.

5.7 SES Main Components

This subchapter describes the components of the SES that consolidate its use as a training and testing tool. The Administrative and User modes are discussed, while the AI, structural and event components are presented.

5.7.1 Administrative Mode

In this mode, a user administrator can access and spawn all the elements and functions of the simulator, while actively participating in the action spawning evacuees, setting the parameters and controlling the various elements of the simulation. The most important administrative features are listed in Table 3:

Administrative mode	Setting the simulation scenario and the initial properties of the simulation up.
	Initiating the evacuation by triggering an initial event such as spawning a fire or smoke.
	Spawning of any hazardous elements or triggering of an event (e.g. ship's listing) in real time after the initiation of the evacuation process.
	Observing the spatial phenomena such as bottlenecks and congestion areas, assessing the effect of counterflow, stairs, and elevator on crowd's movement and behavior, observing the behavior of individual evacuees and the crowds, such as mimic, under panic, herding and stressful conditions behavior, initial response time, leader-follow behavior. A new update should include children and disable people's behavior.
	Collecting extracted simulation numerical data such as the death toll percentage, the death or injury elements, the total number of the escapees.
	Terminating the evacuation sessions.

Table 19. SES Administrative mode features.

5.7.2 Game Modes – Evacuation Scenarios

Moreover, the administrator can configure the initial parameters of the evacuation scenarios by selecting among three game modes. The modes are to be selected based on the purpose of any individual evacuation simulation scenario. When one of the below-listed game modes is chosen the initial simulation scenario configurations are set:

- **Simulation-only mode (SO)**: This simulation mode allows the exclusive use of bots (AI-controlled evacuees) as participants. Administrators can fly across the scene as an invisible and bodiless identity, spawning events, hazardous elements, and even bots. This mode is ideal for the conduction and assessment of evacuation scenarios without the intervention of human users. It is proposed for the collection of data and its assessment, of real incidents, of alternative real scenarios, and the continuous repetition of evacuation scenarios.
- **Single simulation mode (SiS)**: This mode allows the administrator to participate as an evacuee (or crew/rescue team member on later updates) among AI-controlled bots. No other human participants are allowed. The Administrator retains the ability to spawn events, elements, and human characters. This model is proposed for testing locations, elements, and effects of the simulator without the intervention of other human users. It can also provide reliable simulation output.
- **Multiplayer simulation mode (MuS)**: This mode allows the simultaneous participation of many human users (controlling avatars) along with AI-controlled bots. This is a crucial element of SES, as it allows us to assess the effect of the simultaneous participation of bots and humans in the same simulation scenario. It can also allow us to evaluate the degree of realism and the ability of the bots to learn and imitate the behavior of real humans, while effectively evacuating the ship. The maximum number of human users and bots can be set during the configuration phase, but the administrator can increase the number of participants (human users or bots) while the simulation is running. This mode is ideal for the assessment of the human behavior during an evacuation, the evaluation of the simultaneous humans-bots participation, and the assessment of the effects that are spawned, in runtime.

5.7.3 Initial and Runtime Spawning

An administrator may set up some initial effects and elements but can continue spawning at runtime. The Initial Setting and Spawning Phase is implemented before an evacuation scenario starts. During this phase, an Administrator creates a custom scenario based on the initial settings as shown in Table 20.

Setting	Description	Game Mode
AI Bots	A number of AI-controlled bots. These bots are spawned at random locations when the simulation scenario starts.	SO, SiS, MuS
Player's Maximum Number	The number of human users that can participate in a single scenario. This option is available in Multiplayer Mode only. An Administrator can alter this number in order to test the crowd behavior with various compositions.	MuS
Fire Sources	The number of fire sources, the Intensity level which sets the size, and the heat that the fire radiates. These Fire Sources are spawned at random locations when the simulation scenario starts.	SO, SiS, MuS
Smoke Sources	The number of smoke sources, the Density level sets the size and the area that a smoke source occupies. These Smoke Sources are spawned at random.	SO, SiS, MuS
Poisonous Gases	The number of poisonous gas starting points, the Toxicity level set the deadliness of the gas. These Poisonous Gases are spawned at random locations when the simulation scenario starts.	SO, SiS, MuS

Waves Intensity*	The yes and no options define the presence of rough sea or not. The intensity option is going to be integrated later.	SO, SiS, MuS
Ship's List	The check button option defines the presence of the listing or not. The Starting Slope (in Degrees) feature is going to be implemented later. An Administrator controls the listing angle and speed. The guidelines are based on Yosida (Yosida et al, 2014), on ship inclination and its introduction to evacuation simulators.	SO, SiS, MuS
Inlet of Water*	This option defines the presence of rising water or not. The uprising can be set in cm per minute and the next option defines the water as frozen that additionally hurts the evacuees that come in contact with it. This feature is going to be incorporated later.	SO, SiS, MuS
Illumination	An Administrator can choose among the Normal (normal ship artificial illumination), the Alarm Lights (red lights), the Low Lighting (low intensity of lights) or the No Lights (the power is off and there is no artificial lighting in the interior of the ship). The alteration of light conditions affects the bots too, as they are programmed to react like human beings during low or no light conditions.	SO, SiS, MuS
Day/Night	This setting defines the day period providing 2 possible options: Day or Night. The Administrator can choose among Daylight or Night-time conditions.	SO, SiS, MuS
Fog	The option sets the heaviness of the fog around the ship. No Fog options mean no fog at all, Light Fog applies light fog and heavy fog applies heavy fog conditions.	SO, SiS, MuS

Table 20. Initial settings posed by the administrator.

*Settings with an asterisk are going to be integrated into future work.

Figure 35. Evacuees in close contact with a source of fire

Furthermore, the real-time spawning phase settings appear on the top of the Administrator HUD screen after the initiation of a simulation scenario. The administrator can spawn any element or an event. This first effect could trigger the evacuation process if it is perceived by the users. As an example, a bot that can see a fire source needs some time to react (initial response time) and then notifies other bots, triggering an alarm and setting all the bots in evacuation mode. This phase can be activated by a) spawning an element at an observable by the evacuees’ location, b) by triggering the ship list event where the ship begins to slope, or c) by triggering the alarm using the alarm button in the administrative HUD.

Figure 36. Screenshot of the administrator's HUD.

Moreover, runtime spawning allows administrators to directly intervene in the simulation and affect the flow of the events. Any events that should be added after the initiation of a simulation session should be triggered during this phase, such as:

- **Select Spawn Type**: This scroll bar menu allows the administrator to select among fire, smoke, poisonous gas elements or female teen, female adult, female old, male teen, male adult, male old characters (evacuees) and to spawn them by clicking on specific locations.
- **Ship's List**: The same effect as the initial phase, but when it is unchecked the ship's list stops at a specific angle.
- **Ship Lights**: The same effect of the initial phase, but the light's conditions can be changed in real-time.
- **Day/Night**: The same effect of the initial phase, but the option can be changed in real-time.
- **Waves Intensity**: Same as in the initial phase.
- **Inlet of Sea Water**: Same as of the initial phase.
- **Fog**: The same effect as the initial phase, but the effect can be altered in real-time.

5.7.4 Observation

Administrators are also tasked with the recognition and observation of spatial and behavioral phenomena. Phenomena of this type are hard to be recognized by the application itself and therefore we proposed to be observed and recognized by an administrative user with experience and knowledge on evacuation theory. Some examples of the above-mentioned phenomena can be found below:

Bottleneck: A bottleneck denominates a limited area of reduced capacity or increased demand. Pedestrian movement bottlenecks are usually formed by direct capacity reduction (door or corridor). Bottlenecks are of fundamental importance in the calculation of evacuation times and other observables for buildings or structures (Kretz et al, 2006). Computer-controlled evacuees entering a bottleneck zone receive a penalty for their movement and if the congestion is dense the penalty is increased to 100%.

Evacuees in highly congested Bottlenecks areas, that are not completely stuck int0 a crowd, are subject to Rerouting and recalculation of their exit path.

Congestion: Wang et al. (Wang et al, 2015) describe congestion areas such as situations where some agents want to move to the exit quickly by crowding other agents. Since under intense stress people try to move faster than normal, the overtaking and casualty phenomenon usually arises. This phenomenon is very common in emergency situations. Computer-controlled evacuees entering a Congestion zone receive a penalty for their movement and if the congestion is dense the penalty is increased to 100%. Evacuees in highly congested areas that are not completely stuck into a crowd are subject to Rerouting and recalculation of their exit path.

Counterflow: As Yoshida et al. (Yosida et al, 2001) argue after the outbreak of a disaster, several people move against the mainstream of evacuees toward their cabins or seats in order to search for their relatives and gather their belongings, life jackets, etc. This causes a stream of movement directly opposing the main flow toward exits, which contributes negatively to the total evacuation time and overall evacuation conditions.

Climbing stairwells: Encountering stair evacuees reduce their speed, due to the higher effort needed to climb the stairs. The speed is kept being reduced for as long as they struggle to climb a stair moving upwards. The effect is not applied when the evacuees descend a stair and increase their fatigue because of the extra effort they need to make, especially during the elevation of staircases (Chen et al, 2018; Huo et al, 2016).

Movement by elevators: This feature is planned to be implemented in one of the upcoming releases.

Behavior Under Stressful Conditions: (Helbing, et al, 2002) and Pelechano (Pelechano et al, 2005) propose some observable behaviors commonly present during an evacuation. Behaviors such as mimic behavior, leader-following, panicking, child-parent follow-up behaviors can be partially recognized by an administrator, while the output of those phenomena should be reflected in the extracted numerical data. As an example, if the children-evacuees are observed to follow their parents, then we expect lower casualties among this category of evacuees.

5.7.5 Output Data Collection

After the completion of an evacuation session, the administrator may terminate the session. This ends the simulation and processes the results. The next phase is the collection and assessment of the numerical and statistical output data. The categories of this data are shown in Table 5.

Output Result	Description
Starting and spawned evacuees	The numerical representation of the spawned evacuees from the initial phase and the spawned evacuees during the real-time evacuation.
Evacuee's crowd composition	The numerical and percentage representation of the individual categories of evacuees. We display the categories of TM, AM, OM, TF, AF, and OF.
Total safely evacuated	Indicates the total number of safely evacuated individuals and their percentage.

Safely evacuated by category	Indicates the number of safely evacuated individuals and their percentage by category. We display the categories of TM, AM, OM, TF, AF, and OF.
Total casualties	Indicates the total number of deceased evacuees, individuals, and their percentage.
Casualties by category	Indicates the number of deceased individuals and their percentage by category. We display the categories of TM, AM, OM, TF, AF, and OF.
Total injured	Indicates the total number of injured evacuees, individuals, and their percentage.
Injured by category	Indicates the number of injured individuals and their percentage by category. We display the categories of TM, AM, OM, TF, AF, and OF.
Injured by injury cause	Indicates the number of injured individuals and their percentage by injury cause. We display the causes of fire, smoke, poisonous gas, and others.
Exit selection	Indicates the percentage and the number of evacuees depending on their exit selection and category. E.g. Side Door A: Total 10% and 10/100. Men 30% and 3/10 - Women 70% and 7/10.
Evacuation time	Indicates the total evacuation time.

Table 21. Numerical and Statistical Output.

The data can be stored in a slot and/or exported to spreadsheet format for further process and assessment.

5.7.6 Player Mode

The Player Mode is proposed for users or testers of the SES, impersonating virtual evacuees (avatars) during evacuation simulation sessions. The main purpose of those users is to escape the ship, while in critical and dangerous conditions (e.g., fires, smoke, listing). Moreover, a player could assist other evacuees undertaking the role of the leader or the guide. Participation is not frequently met in evacuation simulation applications; therefore, it is considered as one of the most important and innovative features of the SES. The administrator recognizes and assesses the actions of the users while spawning ongoing events. The observed behaviors could be compared with previously collected data, from real evacuations or other evacuation applications. This feature is purposed to assess the deviation of human behavior under real-life stressful conditions. An additional purpose is to study the interaction capabilities of the human user and AI-controller bots and how realistic this interaction is.

5.7.7 Evacuee Type Selection

Based on the Human Factor theory of Disaster Psychology, not all evacuees are the same. Every evacuee type has its own characteristics (Vorst, 2010). In this case, the introduced characteristics are Age and Gender, combined as described herein in detail. The available evacuee types are Teen Male (TM), Adult Male (AM), Old Male (OM), Teen Female (TF), Adult Female (AF), and Old Female (OF). The users are prompted to pick one type and enter the game while they are encouraged to choose an evacuee that matches their age and gender, increasing the realism. An old male user is expected to behave differently compared to a teen female one, based on their different background and experiences. Additionally, taking into consideration Duncan (Duncan et al., 2007) and Heimann (Himann et al., 1988), aging directly affects the speed of a person. Subsequently, the avatars of different ages are applied with different median walking and running velocities. Old Female and Old Male types have the lower velocity (0.26 – 0.27 m/s). Female and Male Teen types are faster than the Old avatars but slower than the Adult ones, mainly because of their shorter limbs (0.67 – 1.0 m/s) (Larusdottir & Dederichs, 2012). Adult Female and Male types are the fastest ones (1.27 – 1.34 m./s). Adult and Old avatars occupy larger volumes, while the Teen avatars are smaller. Teen avatars also have higher pre-movement times as proposed by Lárusdóttir, 7.96 on average (Lárusdóttir, 2014).

Teen Female	Old Female	Adult Female	Teen Male	Adult Male	Old Male

Figure 37. Avatar Types

For the creation of the models Mixamo was used for the basic models and the animation and then the models and the animations were imported to Unreal Engine 4. A typical evacuee (computer-controlled or user-controlled) is composed of the Character Mesh, the Collider, and the Cameras. The character mesh is the whole body of the evacuee and depicts the outlook of the user and defines the proportions, although it is not the feature that defines the area occupied by the character. The Collider, though, creates a barrier that defines the area that it is occupied by the character, and it is typically Cylindrical. The collider is treated as the "personal space of the character" and triggers all the collision events, while allowing the character to interact with other objects and characters. Figure 38 displays the top view of the Character Mesh and clearly defines the collider in a top-down perspective. Figure 39 displays the right view of the character and the collider.

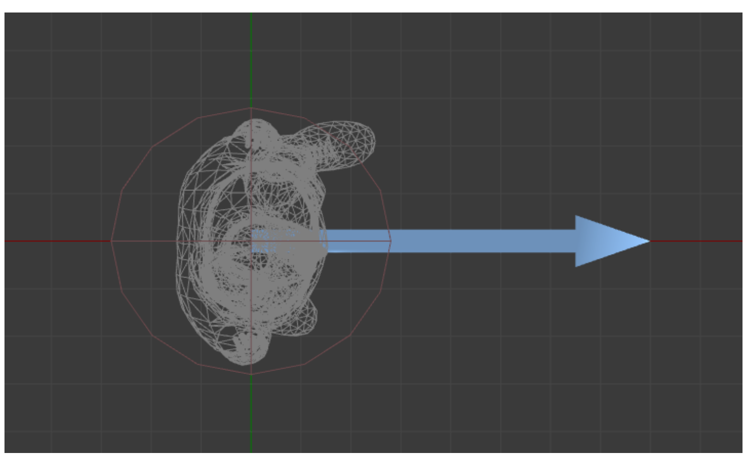


Figure 38. Character, Colliders and Forward Vector

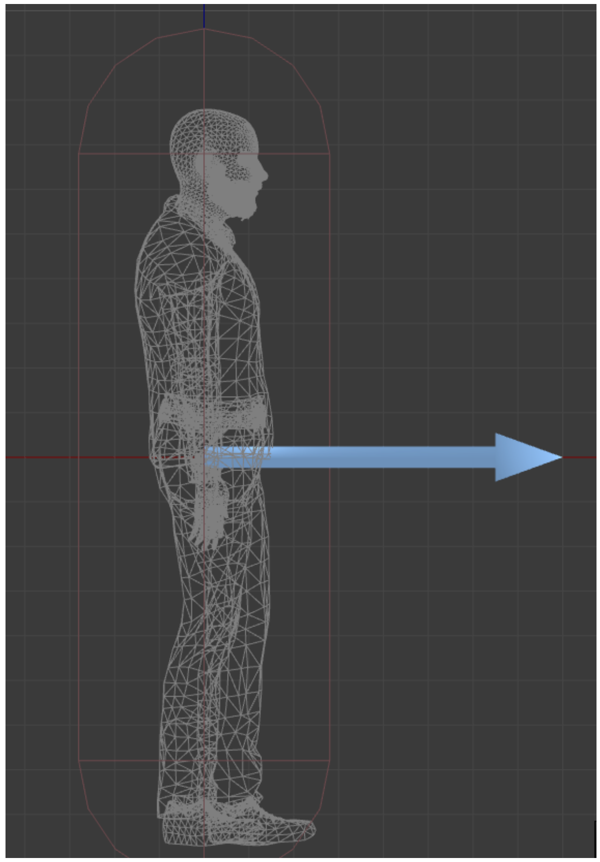


Figure 39. Right View of the Character, the Collider, and the Forward Vector

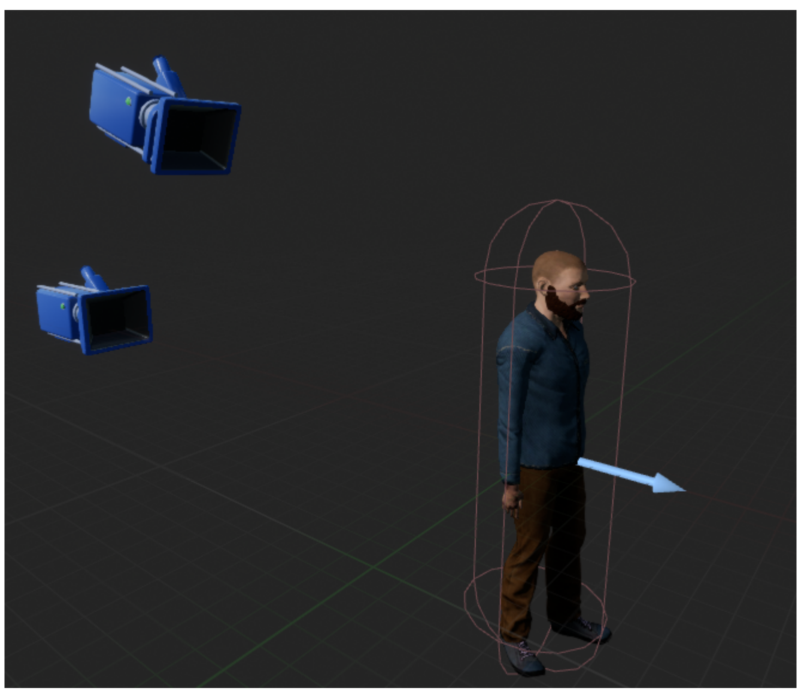


Figure 40. An Adult Male Character from SES

The Forward Vector is a vector that defines where the character is facing, and it is a useful element that helps the animation, movement, and ray casting of the characters. The dual cameras are both movable. The users can move them around the player holding the Shift key and moving their mouse. They can also pick between the two cameras, once placed over the character and one place at its back. Moreover, the camera can zoom-in and zoom-out allowing the users to place them wherever they wish.

All the characters are implemented through the base 0_base abstract class (Blueprint), which hold all the common properties and then the different character types are implemented with their own particularities according to the character's type. Each distinct character type is created by a separate derived class (Teen Male (TM), Adult Male (AM), Old Male (OM), Teen Female (TF), Adult Female (AF), and Old Female (OF).

The characters are fully interactive and when they encounter other elements start to be applied with their effects. The same stands when the evacuees collide with other evacuees but in this case only spatial effects are applied. The approach is different in pathfinding and danger detection. The computer-controlled bots have a Field of View (FoV) of 120º that covers the combined FoV of both eyes and its origin is placed at the height of the bot's eyes (Ball, et al.,1988; Chen & Aggarwal, 2009, December; Costella, 1995). The bots can detect dangers and exits with Ray Casting, where Rays detect all the exits and dangers and the algorithm decides the best path, based on this data (more about the Algorithm in a following subchapter). When an evacuation session is initiated, bots start searching for possible exits, while they are also searching for dangers (e.g., fires, smoke, etc.) and if they come close to those dangers can avoid them, if they are not restricted by other means. The bots will approach a dangerous spot only if any other path has been blocked and the danger is blocking their sole exit.

Figure 41. Evacuees trying to avoid a fire source in the restaurant area in SES

5.7.8 Spawning

An evacuee is spawned in a random location inside the ship. An evacuation: (i) initiates immediately or, (ii) could initiate when an evacuee detects an imminent hazard (fire, smoke, etc.) or (iii) initiates if the slope of the ship reaches a high level. A user can hear sounds and voices, from sources close to him.

How clear those sounds and voices are depending on how distant and how intense those sources are. The users can switch from a third-person perspective to a first-person perspective and vice versa. A third-person perspective viewing point is set over the head of the avatar, while a first-person view is over the line of the eyes.

Alternatively, the evacuees may be spawned by clicking to a valid location after selecting the evacuee type. A valid position means a location that is not a vertical or too steep surface, an object such as a chair, and a non-solid surface. The newly spawned evacuees have the same abilities as the existing evacuees and behave similarly. If the evacuation has started, the newly spawned evacuees start to act right after their respective response time.

5.7.9 Health, Fatigue, and Display

The human users are provided with information on the condition of their Avatar, and the player's HUD. Three indicators are listed below:

Health Bar: The health bar reflects the physical condition of the avatar. While direct and prolonged contact with a hazardous element (fire, poisonous gas) should completely deplete this bar, an indirect and instantaneous one should reduce only a portion of it. This bar drops while the avatar is in contact with a fire source inside a smoke source or a poisonous gas or is hit by objects, such as chairs and tables. If the health bar drops under 50% the avatar is disallowed from jumping and running, while its walking speed is significantly decreased. If the health bar reaches 0% the avatar is dead and the user should exit the simulator or remain as a spectator.

Fatigue Bar: SES follows the concept of Fatigability and the state level of fatigue, taking into consideration the condition of an evacuee before the incident and during the ongoing situation (Enoka & Duchateau, 2016). As defined in Chapter 3, a Fatigue bar or numerical display informs the user regarding the avatar's endurance on physical challenges such as running, jumping, climbing, etc. While the avatar runs or climbs stairs, this bar increases. When it reaches 100%, the avatar is unable to run, jump or climb stairs and reduces its walking speed by 50%.

Breathing Indicator: A breathing indicator updates the user about the avatar's breathing pace. If any difficulty occurs, the indicator changes color and/or rhythm. As explained in Chapter XXX, monitoring the avatar's breath rate informs the user about toxic gases and/or excessive fatigue. This feature will be implemented in an upcoming release.

5.7.10 Player Controls

An evacuee moves and acts using mouse and keyboard keys as listed in Table 22. All the evacuee types share the same controls. The keyboard controls mainly the movement of the avatar with a combination of the traditional (W, S, A, D) key to control the movement direction, the Left-Shift for increasing the speed of the evacuees, the C to crouch and the Spacebar to Jump. The E key uses items, and the Left Mouse button activates functions, such as alarms. The Mouse works mostly with the camera and the camera rotation is controlled by the mouse movement, while the zoom-in/zoom-out functions are controlled with the Mouse Scroll Button.

Function	Key

Walk Forward	W
Walk Backwards	S
Walk Left	A
Walk Right	D
Run	Left-Shift
Jump	Space Bar
Crouch	C
Use	E
Activate	Left Mouse Button
Camera Rotation	Mouse X-Y axis
Camera Zoom-in/Zoom-out	Mouse Scroll Button

Table 22. Player Controls (SES)

5.8 Evacuation area

SES is characterized as a Three-Dimensional Evacuation Serious Game and Simulator for ships of the Passenger Ship category, for passenger training, although if the parameters are modified it could be potentially used for other categories such as cargo carriers, container ships or fishing boats, recreation vessels (Blix et al., 2015). The main game level is the GameMap level, which includes the virtual environment and the testing ship. SES uses (as its evacuation area) a model of the RO-RO Passenger ship EXPRESS SAMINA (Figure 4) modified, based on the official dimensions provided by IMO. The ship has a gross tonnage of 4555 tons, a length of 115 m and a Breadth of 18m and these features have been implemented in the simulation. EXPRESS SAMINA has two decks: the lower and the upper deck. The compartments of the lower deck are three cabin areas with multiple cabins connected by two parallel corridors and the lower deck lobby.

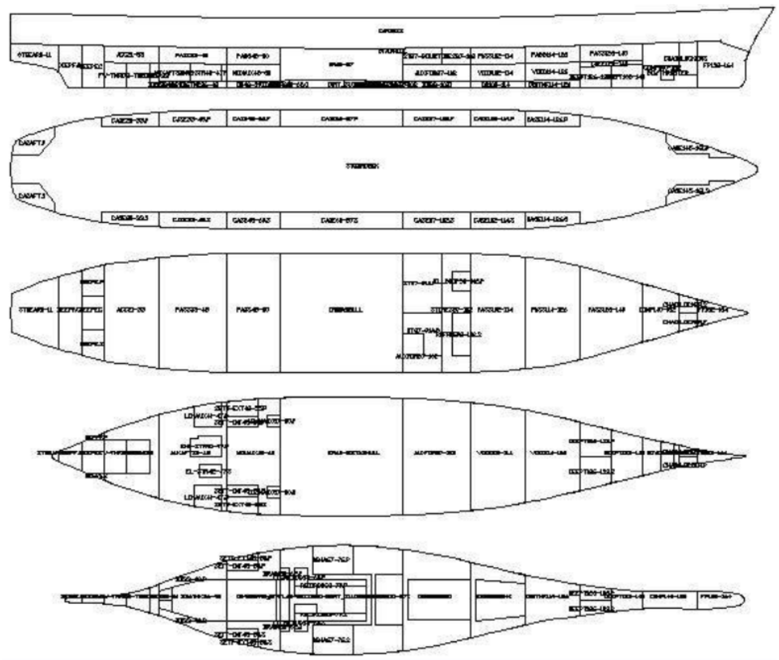


Figure 42. Views and decks of the passenger RO-RO ferry EXPRESS SAMINA.

The upper deck’s main compartments are the two large sitting areas, the upper deck lobby, and the restaurant. Six stairwells allow the passenger to commute between the two decks. The four doors leading to external parts of the ship (balconies), are located at the upper deck, and thus are considered as the exit points. After reaching any of those exit points, an evacuee is considered as safe. Two exit points are located at the stern, while the other two are at the bow of the ship. In this regard, the pathways are based on the pathways of an existing ship and the assessment of the results is considered based on this assumption.

The ship’s interior is equipped with several objects and items that suit the interior of a passenger ship and are listed in Table 23.

Equipment	**Description**
Built-in beds	Located exclusively inside the cabins, beds are immobile objects, bound to the structure, restricting the movement in the interior of the cabins though the evacuees can step on them, if they jump.
Tables	Located especially in the restaurant area, tables are also immobile and bound to the structure, restricting the movement, and can be climbed after a successful high jump.
Chairs	Located in various locomotives are movable items, either by evacuees or by any listing or movement of the ship. Chairs can be a nearly impassable obstacle if they block a narrow corridor or an exit.
Speakers	Located at both decks, the speakers broadcast alarms, alerts and messages.
Lights	Spotlights are the main illumination sources for the interior of the ship. Altering their intensity and color, and administration can switch from full illumination to partial illumination, no illumination or alarm illumination.
Doors	Unlocked doors may automatically open if approached by an evacuee. Locked or stuck ones won’t open without the intervention of a crew member.

Table 23. Ship equipment used in SES.

Figure 43. Ship's Interior (Upper Deck) in Perspective View

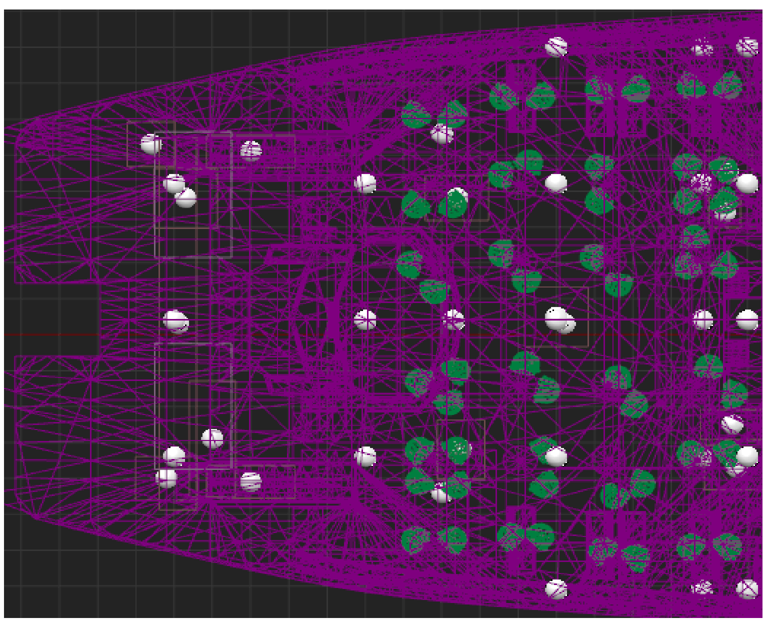


Figure 44. The Express Samina model Restaurant in a top-down view. The green dots depict the tables, and the white spheres depict the light sources.

5.9 AI Behavior and Movement

AI Behavior is heavily influenced by the Human Factor theory. The AI implements elements such as the evacuation refusal, in the form of initial response time, which affects about 20% of the evacuees, during the Impact Phase (Vorst, 2010), therefore the main evacuation phase, when the impact of the disaster has been fully developed and all the human characteristics such a hearing, vision, social forces influence and route selection.

One of the most important features of SES is the simultaneous presence of AI-controlled Bots and human users. The AI system controls the behavior and the actions of bots, aspiring to simulate regular human evacuees. This feature enables the researchers and the users to assess the behavior and movement of crowds composed of real players and bots and the deviations that can be noticed, compared with systems that only include bots or human users. They can also assess how capable AI-controlled bots are to really behave as real human evacuees and how they can interact with other bots or real human users.

The AI System was developed using the UE4 build-in AI system. For the Behavioral aspect, the algorithm implements a combination of the Affiliation and Protective Action Decision (PAD) Models. The evacuees are treated as individuals, but they actively interact and cooperate with others, in case of leader following or family ties. More specifically, it was based on the development of Behavior Trees (tree-like flowcharts for Behavior), Blackboards (store important locations or persons), and special-purpose programs called Services, Decorators, and Tasks. Behavior Trees are used for developing a tree-like structure of actions a bot may take. Blackboards are attached to the Behavior tree storing locations, and persons. Finally, Services, Decorators, and Tasks are attached to behavior trees, updating, and enhancing them with any newly collected information. The bots may collect information using their senses (Hearing and Sight) and process this information so that they act accordingly. As an example, if a bot sees a blocked door it will not select a route that passes through that door, and instead it will start searching for alternative free routes. The features of the SES bot's AI decision-making system are described below.

Hearing**:** Bots can hear sounds, broadcasted from a source located close by and only if the intensity is high enough. This feature is experimental and will be fully implemented in future releases. The alarm sounds will instigate an evacuation, for sure, after applying the Initial Response time to the bots.

Sight**:** Bots can see within a field of view of 180^{o} degrees centered right in front of them (forward vector). This angle simulates the eyesight of most adult populations. When the evacuees turn their FoV is shifted to match their direction. When the evacuees' sight is blocked by objects or other evacuees, they are unable to recognize an exit and may start searching for another visible route (Dynamic Rerouting).

Initial Response Time (IRT)**:** When a potentially dangerous incident, such as a fire, breaks in, the bots need a random initial response time before they start to react. This Response Time Frame varies from 1 to 5 seconds, based on the particularity of every evacuee (Zhao et al., 2009) and slightly increased for Teen evacuees, as mentioned above. Bots cannot take any action before the expiration of the Response Timeframe. The initial response time aspires to simulate the time needed to realize, evaluate, and eventually react after the outbreak of a disaster. To implement IRT on human evacuees, the human bots are halted for their assigned IRT, right after the initiation of the evacuation.

Social Forces Effect**:** Studies argue that, after the outbreak of a disaster all the bots are searching for crew members, relatives, or leaders in their immediate area (Nilsson et al., 2009). The Leadership feature follows the model proposed by Quingge & Can (Qingge & Can, 2007). The leaders are assigned at the beginning of a simulation session and attract the evacuees near them. The influence is reversely proportional to the distance between the leader and the evacuees. Those followers imitate the actions of the "Leaders", although they may abandon them if the Leaders prove themselves unreliable, leading them to congested areas or blocked doors. Leadership behavior initiates, if the Yes flow at the "Visible Crew or Relatives or Leaders" is followed (see Figure 45).

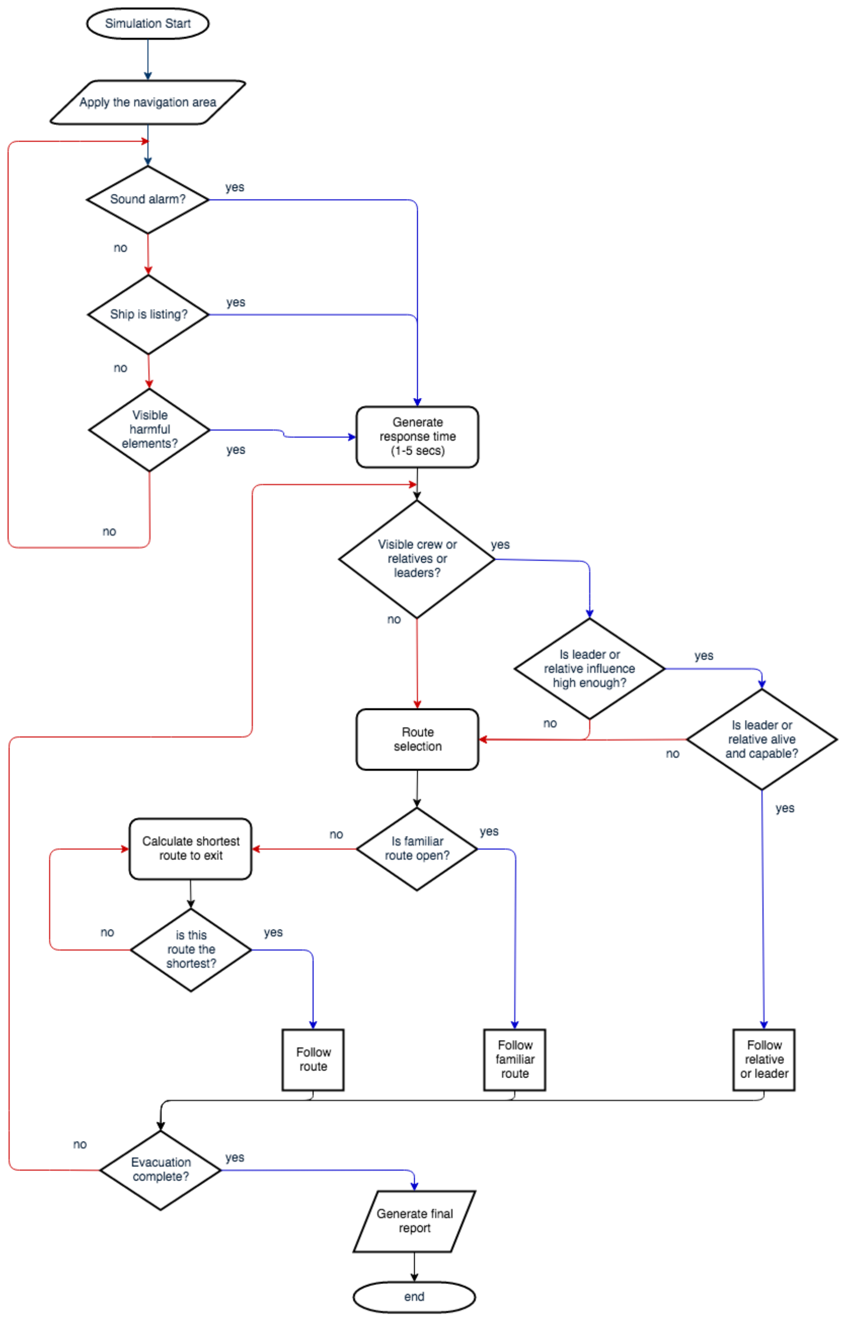


Figure 45. The decision-making algorithm of AI-controlled bots.

Route Selection**:** The passengers evacuate using escape paths based on SOLAS regulation II-2/13, adjusted to match the needs of the simulator, the words in the symbols are printed in English and Greek (Express Samina service area was the Aegean Sea in Greece and most of the passenger were of Greek origin). Therefore, the escape paths are designated and labeled, though recent studies have shown that the passengers tend to ignore signs and select the shortest or more familiar path. The routes are continuously calculated, updated, and compared with previous ones. Therefore, a bot starts an evacuation scenario searching for crew members or, if a teen, for adults into their field of view. Then, the algorithm starts scanning the area for the non-blocked and closest exits of the area. In case, a bot is jammed into a crowded location, while it is following a selected route moving toward an exit or an area, after 5 seconds of very low speed or immobility it starts searching for alternative unblocked routes around it. This feature is called Dynamic Rerouting. For the selection of their route (initial or rerouted) the bots follow a sequence of steps instructed by the Behavioral and Movement Evacuee Algorithm (BMEA), as listed below and in the below formual, in more detail:

- **Follow-up (F):** The first action taken by the evacuees is to follow a Leader. Leaders could be crew members or parents, causing the adult Bots to mainly follow the former, while kids tend to follow the latter.
- **Route Familiarity (RF):** How familiar is an evacuee with an escape route. Studies have shown that the evacuees prefer to use as an escape route the one they previously followed to arrive at their current location. In SES the evacuation process starts either by a visible threat or by sounding an alarm. If a bot has wandered next to an exit before the alarm sounds, then this exit is prioritized, if it is not blocked and in equal distance compared to other exits..
- **Blocked or Not (B):** Evacuees usually choose the closest clear (unblocked or unlocked) exit, following the shortest clear path. An obviously closed or locked door, a route blocked by a piece of furniture, fire, or smoke, is ignored unless it is the solely available route. The evacuees are programmed to evade dangerous areas and elements, although they will walk through those areas if there are no other options.
- **Estimated Selected Route (ESR):** The Estimated Selected Route is the chosen escape route, towards the Estimated Selected eXit (ESX). The ESX is the exit that has been picked by the BMEA. Bots calculate the distance and choose the nearest, clear, passable exit path. If an ESX is reached, then the flow returns to the top, after the “Generate Response Time” node and it is searching for a new visible exit. This iteration algorithm format is necessary, due to the compartmentation structure of the ship, where the final exit is usually not visible, but could be into different levels and far away. Therefore, the bots should follow some waypoints towards their presumed final destination. The ESR is calculated by comparing the coordinates of the bot (L_B) and all the observables (by the bots), clear exit spots (L_E). The calculated distances are then compared and the shortest one is chosen. The functions are displayed below:

$$D^{1,2,n} = L_B^{\ 1,2,n} - L_E^{\ 1,2,n}$$

$$ESR = M(D^1, D^2, D^{n\ldots})$$

- **Dynamic Rerouting (DRr)**: This is an optional stage that is triggered if the bot is stuck to the same location for more than 5 seconds or if it cannot discern a visible exit or if the ESR or ESX is blocked. During this stage, a rerouted bot is disengaged by its current target and starts searching for a new ESX and subsequently a new ESR. In fact, the DRr moves the flow of the

BMEA, at the "Route Selection" node. The algorithm iterates, until an open, clear path is visible to the user to follow.

5.10 Conclusions

The Ship Evacuation Simulator was developed with Unreal Engine and the algorithms were written exclusively with Blueprints. It meets all the criteria that makes an application a Serious Game with many Evacuation Simulation elements specialized in Passenger Ships. Detailing, it supports a 3D virtual environment and a model of the Express Samina liner, several elements and evacuees may be spawned in real-time or in the beginning of a session, spatial and behavioral phenomena such as congestions, bottlenecks, social influence have been implemented and the results are retrieved and stored for further assessment and evaluation. If SES is installed on different devices, it could be used in Multiplayer mode where the participation of multiple users as evacuees is allowed. The users can join or create evacuation sessions by selecting one of the six available avatars. Each avatar has its unique features, such as speed and health, so that it is differentiated from the others. The computer-controlled avatars follow the experimental data that have been gathered will be reviewed and assessed in the next chapter, where the Data Validation can also be found.

5.11 Summary

A Three-Dimensional Multiplayer Gamified Edutainment-based Ship Evacuation Serious Game - Simulator, named Ship Evacuation Simulator (SES), was developed with the use of the Unreal Engine 4. The Simulator can execute evacuation sessions, in real-time, with a variety of options that range from the lighting to the number of the evacuees. A novel algorithm controls the movement and the behavior of the bots.

Chapter 6

6.1 Conclusions

After thoroughly testing the Ship Evacuation Simulator, other evacuation simulators and studies on, human psychology and behavior under stressful conditions, evacuation incidents and disasters and evacuation simulations, the application can represent the conditions and the motion of a passenger ship, while can credibly simulate the physical qualities, the actions, and the movement of human-like evacuees.

6.2 Application Validation and Experimental Results

The architecture described in previous sections and used to implement the simulator SES, is the basis for allowing a lightweight simulation environment, created with a game engine where designers and operators can train their monitoring, planning, and re-planning skills without the need of a powerful machine or specific software installation. To ensure the proper functionality and scalability of the planned architecture, it was necessary to carry out some tests. To test SES, some experiments have been executed to show that the application hardware requirements are low, so any modern computer can run and visualize the evacuation sessions correctly. The SG has been executed using different platforms (desktop and laptops) in two different operating systems (Windows and Linux) but most of the testing was done on Windows 2010. All of them have performed around a constant 30 Frames per Second (FPS) rate. However, SES cannot be currently executed on mobile devices and tablets, but future implementations could be transferred to such devices. Several Simulation-only, Single Mode, and Multiplayer scenarios were conducted for the needs of this paper. A PC with a minimum of 16GB of RAM, can run a scenario, with up to 1000 bots, without significant performance issues. The total number of evacuees is expressed by the $n=n_h+n_b$, where n is the total number of evacuees, n_h is the total number of human evacuees, and n_b the total number of computer-controlled bots. For more than 1000 bots ($n>1000$), the use of more powerful computers is proposed to avoid technical difficulties.

The validation of the SES was confirmed by comparing the data of the evacuation session with data from real incidents. After running the simulations, the initial settings were modified and tested with results and incidental and experimental data and reviewing if the outcome would be the expected one. As an example, if many evacuees are spawned next to a narrow corridor the outcome, based on existing incidents, should be the formation of an arch by the bodies of the congested evacuees.

6.3 Simulation-only Mode

Five evacuation sessions were conducted with 600 Bots spawned in the interior of the ship. Most bots (*n=400)*) were spawned at the upper floor (restaurant, upstairs lobby, and seating areas) and the rest (*n=200*) were spawned at the lower floor (cabins and downstairs lobby) randomly (see Figure 46).

Figure 46. Bots – evacuees attempt to escape the lower deck (left), fire evasion close-up screenshot (right).

The conditions and the results varied depending on the spawned elements (fire, smoke, poisonous gases) and the duration of the session. Each session lasted for 10, 15, 20, 30 and 40 minutes respectively and the last one was terminated when all evacuees had safely evacuated the ship or had perished.

The initial response time was triggered normally and the bots - evacuees reacted after a period of time varying from 1 to 5 seconds. Bots-evacuees attempt to recognize an observable leader-bot that has been previously assigned by the administrator. The recognition was difficult due to the density of the crowd, the intensity of noise, and the large size of the ship that limited the ability of the bots to see or hear someone. Only 14% of the bots eventually follow a leader-bot. Moreover, bots walked or ran following the shortest estimated passable route, after failing to follow a leader. If the shortest route was blocked, 78-95% switched to the next shortest route. However, 5-22% insisted on following the blocked route.

Some evacuees encountered exit or warning signs and most of them followed the instructions. Sometimes following those signs led these bots to select closed or blocked routes. The recognition of exit signs was difficult because of the density of the crowds. A useful conclusion is that if all the evacuees are directed to follow a specific route, this route could be blocked by the crowds of the evacuees.

Figure 47. Congestion and Arch Formation in front of a Door (low visibility because of moderate smoke.

Figure 48. Arch Formation (Bottleneck) and Dynamic Rerouting.

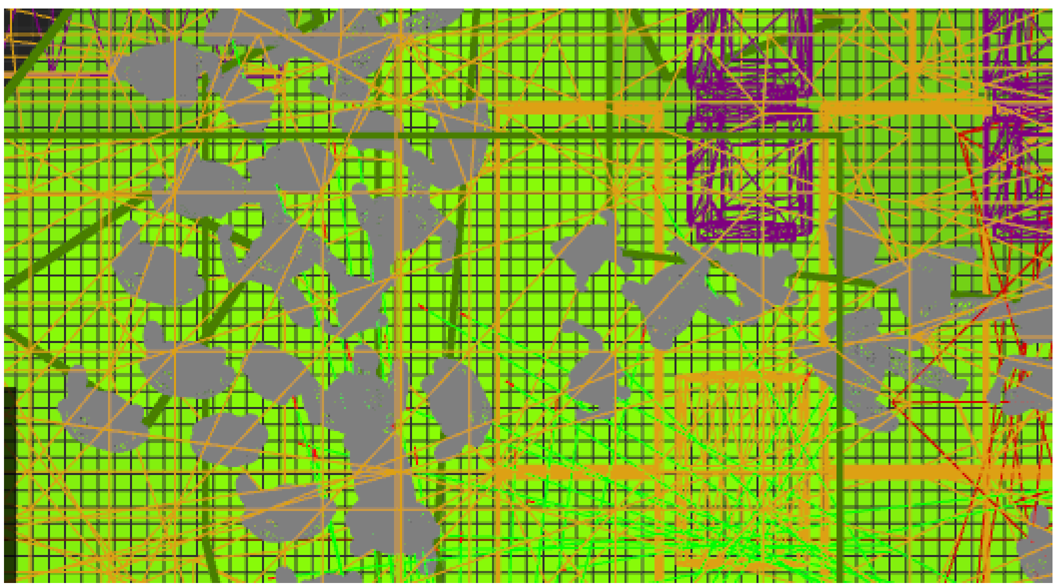


Figure 49. Top-Down Bottleneck in front of a door (the evacuees are the grey spots)

Congestion areas appeared near or in front of doors and near or on stairs as was expected, blocking the path, and significantly reducing the evacuation speed (Figure 50 and Figure 51). The main contributor to congestions was the space occupied by the bodies of the evacuees, which blocked the area restricting the movement of other evacuees. Moreover, objects (such as chairs and benches) blocked or simply occupied an area making the movement more challenging and the space smaller. The areas where Congestions are commonly found, are the entrance of doors and corridors. The results have shown that a lower number of evacuees significantly reduces congestion, as the main cause of congestion is the movement of numerous evacuees into the same area. Larger evacuees (e.g., Adults) occupy more space and are more prone to congestion, while smaller evacuees (e.g. Teens) are less prone due to their small size.

Evacuation Scenario	Time	Survival Rate	Number of Evacuees (n)	Number of Congestions	Evacuees involved in Average
1(s)	No Time Limit	90%	50	1	6
2(s)	No Time Limit	86%	100	3	45 approx.
3(s)	No Time Limit	83%	200	8	120 approx.
4(s)	No Time Limit	96%	400	12	200 approx.
5(s)	No Time Limit	91%	600	22	450 approx.

Table 24. Number of Evacuees and Congestion

Figure 50. Congestion next to a corridor

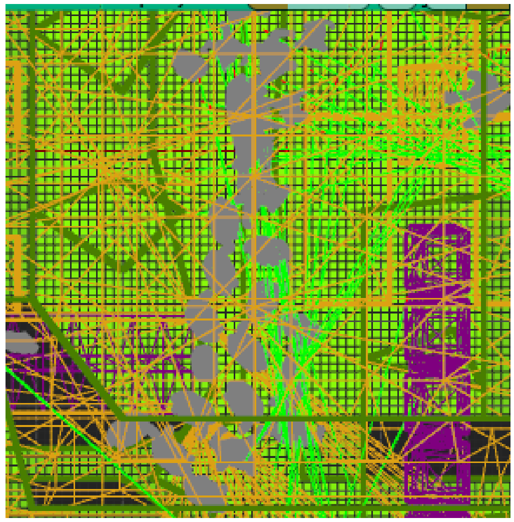


Figure 51. Top-Down Congestion in a Corridor (the evacuees are depicted as gray spots)

Counterflow triggered by some bots - evacuees moving against the main flow, affected the speed of the bot's composed crowds, blocking entrances and disrupting the movement of other evacuees. When the counterflow effect was suppressed by the administrator (even though some bots were moving at the opposite route following their route) the evacuation speed was increased by up to 22% on average. The ratio of the bots-evacuees that survived varied from 14% to 88% depending on the scenario. The injured evacuees and teen evacuee types had a lower Survival Rate (SR) due to their decreased speed. The number of the Counterflow incidents and the involved evacuees are shown in Table 25. Higher numbers of evacuees generate more Counterflows, composed of passengers trying to move against the main stream of evacuation. As the number of evacuees and Counterflows increases, the Survival Rate drops proportionally. The SR of 81% for 50 evacuees drops to 60% when the number of evacuees is increased to 600. The last note is that when a time limit is introduced the SR drops significantly up to 18%, a drop of 42%, as is clearly displayed in Figure 52, where a sharp drop is apparent when a time limit is introduced, due to the additional delays introduced by the Counterflow.

Evacuation Scenario	Time	Survival Rate	Number of Evacuees (n)	Number of Counterflows	Evacuees involved in Average
1(c)	No Time Limit	81%	50	1	6
2(c)	No Time Limit	74%	100	2	45 approx.
3(c)	No Time Limit	74%	200	4	120 approx.
4(nc)	No Time Limit	67%	400	8	200 approx.
5(nc)	No Time Limit	60%	600	14	450 approx.

6(nc)	10 min	18%	600	18	500 approx.

Table 25. Evacuation and Counterflow

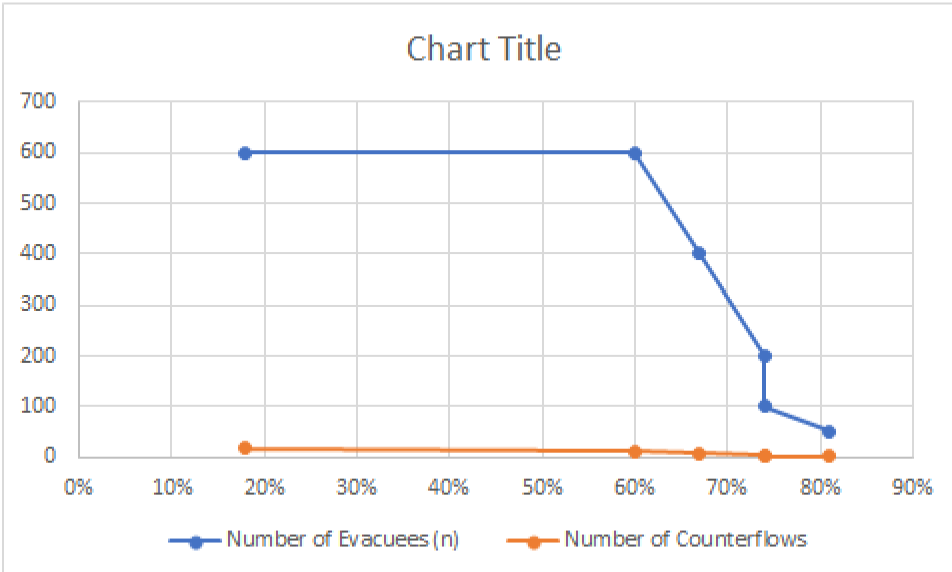


Figure 52. Evacuation and Counterflow

The Evacuation scenarios use information from the Express Samina disaster such as the number of passengers and the time of the incident (Goulielmos et al., 2009; Niininen & Gatsou, 2008; Gatsou et al., 2005), although all the scenarios presented in this work have been conducted with daylight conditions. More specifically, when the administrator increased the number of the real-time (or initially) spawned elements such as fires and smoke, the survival ratio of the evacuees dropped. The longest evacuation sessions resulted in minimized casualties (under the same conditions). When the evacuation time was limitless the Survival Rate in three scenarios was 90%, 86%, and 85% with the presence of instigators (see Table 26). The 10- and 15-minutes evacuation times made the survival rate drop dramatically. The instigators for both scenarios were Fire. The Survival Rate for the 15 minutes was 47% and for the 10 minutes 30%, The time limit is set in case the ship capsizes or is fully immersed under the water, where the escape is considered extremely unlikely and the continuation of the evacuation process almost impossible. After the expiration of the evacuation time, all the non-escapees are treated as deceased. Therefore, this critical drop in the Survival Rate highlighted the influence of limited time on the evacuation process and thus Evacuation time is considered proportional to the SR.

Evacuation Scenario	**Time**	**Survival Rate**	**Number of Evacuees (n)**	**Instigator**
1	No Time Limit	90%	472	Fire
2	No Time Limit	86%	472	Fire & Smoke
3	No Time Limit	83%	472	Fire, Smoke & Light Ship Movement

4	15	47%	472	Fire
5	10	30%	472	Fire

Table 26. Evacuation Time and Survival Rate in Single-Player Mode

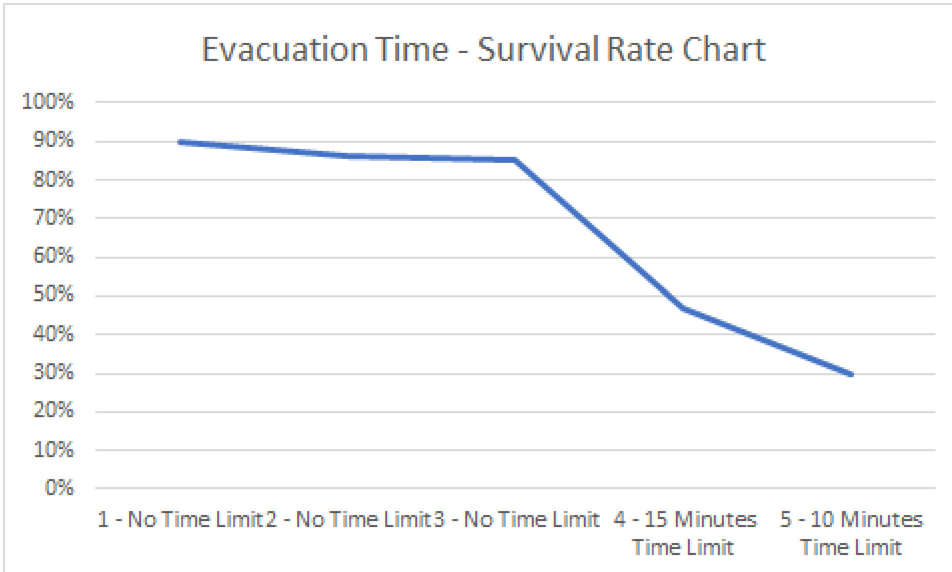


Figure 53. Evacuation Time - Survival Rate Chart in Simulation-only Mode

Scenario	Number of Evacuees (n)	Evacuation Time Limit (minutes)	Survival Rate
Scenario 1 - Express Samina Accident (September 2000)	472	45	88%
Scenario 2 - Express Samina Accident (September 2000)	472	45	85%
Scenario 3 - Express Samina Accident (September 2000)	472	45	86%
Scenario 4 - Express Samina Accident Daylight	472	45	88%
Scenario 5 - Express Samina Accident Daylight	472	45	89%
Scenario 6 - Express Samina Accident No Lights	472	45	55%
Scenario 7 - Express Samina Accident No Lights	472	45	43%

Scenario 8 - Express Samina Accident No Lights	472	45	44%
Scenario 9 - Express Samina Accident No Lights	472	45	21%
Scenario 10 - Express Samina Accident No Lights, Increased Capacity	600	45	19%
Scenario 11 - Express Samina Accident No Lights, Increased Capacity, Limited Time (September, 200)	600	30	12%
Scenario 12 - Express Samina Accident No Lights, Increased Capacity, Limited Time.	600	15	14%

Table 27. Evacuation Time and Survival Rate in Simulation-only Mode

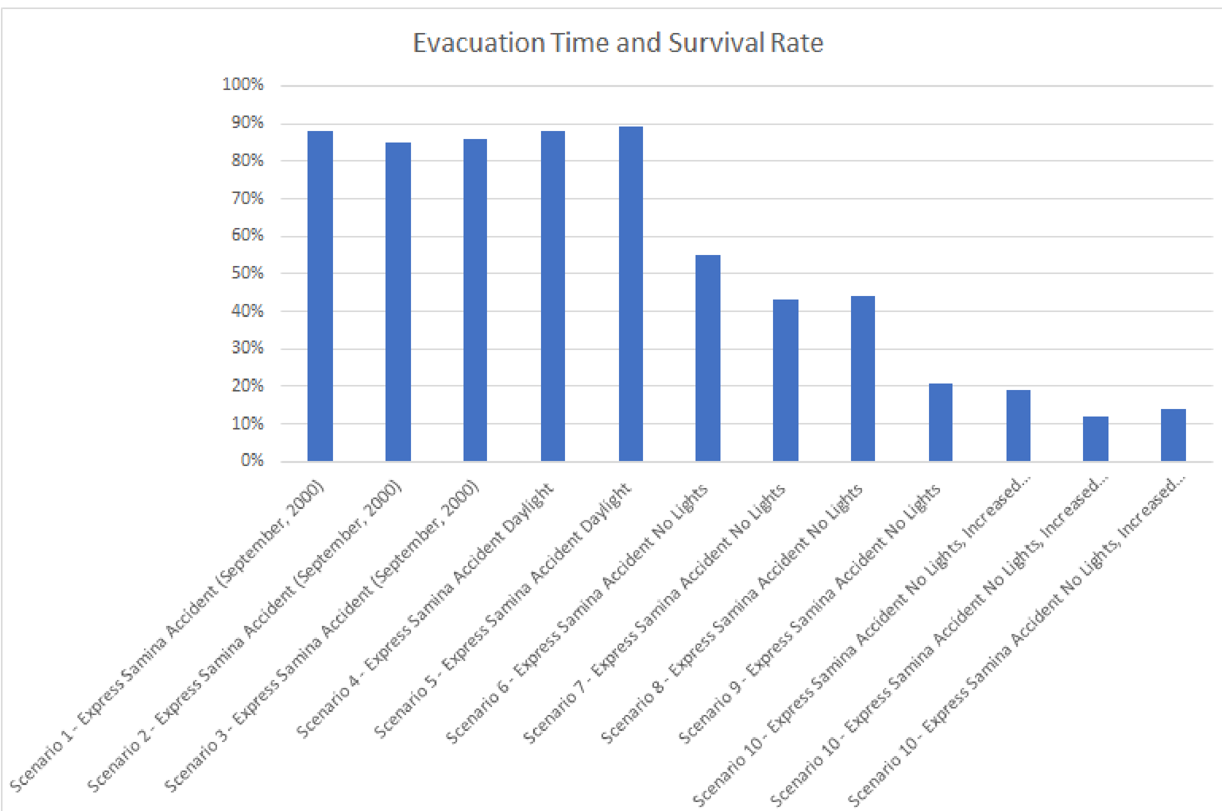


Figure 54. Figure 54. Evacuation Time and Survival Rate

6.4 Single Player Mode & Multiplayer Mode

Five evacuation sessions were conducted with 600 (n = 600) bots and the administrator (Figure 7). No events were triggered while the administrator was participating as a player. Again, most bots (*n=400)* were spawned at the upper floor (restaurant, upstairs lobby, and seating areas) and (*n=200)* were spawned at the lower floor (cabins and downstairs lobby) randomly. All the events and the elements were triggered or spawned before the scenario started.

Figure 55. Bot – Evacuees attempt to escape toward an upper deck exit (left), evacuees attempt to evade a source of fire (right).

The overall results are listed below:

- The bots' survival ratio is increased; no events and elements are triggered or spawned in real-time.
- The human - bot interaction was observed as it was expected, as multiple bots followed the human user's avatars.
- Human users familiar with first-person shooter games have an increased SR up to 60%.
- Human users familiar with the interior of the ship have increased the SR up to 30%.
- Regarding the initial reaction time, the behavior of the human users was similar to the AI-controlled bots. After the breaking of an event, most users evaluated the situation for a timeframe from 1 to 5 seconds before taking any other action.

Fire scenarios were conducted with different settings and the same number of evacuees. The human-controlled and computer-controlled avatars behaved similarly to spatial phenomena as congestions and bottlenecks were formed similar to the ones at the Simulation-only mode. The SR with No Time Limit was slightly improved from 90%, 86%, and 83% to 94%, 95%, and 91% respectively. This is an indication that the computer-controlled bots have acted similarly to human users, whereas the human users tried to work around the system resulting in slightly better results. When the time limit is set to 15 and 15 minutes the SR drops to 47% and 30% drops to 42% and 22% respectively, indicating that the human users were affected by anxiety and could not evacuate in time. No significant difference was observed, when Passengers Ships usually carry families and young people to their homes and vacations.

Evacuation Scenario	Time (minutes)	Survival Rate	Number of Evacuees (n)	Instigator
1(m)	No Time Limit	94%	472	Fire
2(m)	No Time Limit	95%	472	Fire & Smoke
3(m)	No Time Limit	91%	472	Fire, Smoke & Light Ship Movement

4(m)	15	42%	472	Fire
5(m)	10	22%	472	Fire

Table 28. Evacuation Time and Survival Rate in Single Player Mode

Adult Evacuees had a lower Casualty Rate than Old and Young evacuees. Adults Evacuees have a Casualty share of 26% to 13%, while Teen ones 36% to 25% and old from 62% t0 42% The results are discussed in the next chapter.

Evacuation Scenario	**Time (minutes)**	**Adult Casualties**	**Old Casualties**	**Teen Casualties**
1(m)	No Time Limit	26%	38%	36%
2 (m)	No Time Limit	22%	42%	20%
3(m)	No Time Limit	23%	43%	19%
4(m)	15	14%	56%	30%
5(m)	10	13%	62%	25%

Table 29. Casualties Distribution among Evacuee's Types

For further validation of the HCCo model, five evacuation scenarios were executed, with experienced gamers as testers. With 6 testers we reduced the number of the total evacuees to 20, 50, 120, 220 and 472 (including the testers). The results indicated that the SR for Evacuation Scenarios 1,2 and 3 were slightly increased from 94%, 95% and 91% to 96%, 96% and 95% respectively, as well as for the 15 and 10 minutes from 42% and 22% to 50% and 22% respectively. This increase is not a significant change and verifies the capability of the bots to act realistically and the human players to behave as real evacuees in evacuation incidents. As we increased the number of total evacuees from 20 to 50 to the SR remained the same as no significant Congestion, Bottlenecks or other spatial phenomena were observed. When the number of evacuees was increased to 114 the SR fell from 96% to 77%, but the Light Ship Movement was implemented. The ship movement affected the human users more than the computer-controlled bots, which seemed almost unaffected. When the number of evacuees was increased to 220 and 472, the SR fell significantly to 50% and 29% respectively. This significant difference is attributed to the congestion and the Bottlenecks next to corridors, doors, and stairs.

Evacuation Scenario	**Time (minutes)**	**Survival Rate**	**Number of Human Evacuees(n_h)**	**Number of Bot Evacuees (n_b)**	**Instigator**
1(m)	No Time Limit	96%	6	14	Fire
2 (m)	No Time Limit	96%	6	44	Fire & Smoke
3(m)	No Time Limit	77%	6	114	Fire, Smoke & Light Ship

					Movement
4(m)	15	50%	6	214	Fire
5	10	29%	6	466	Fire

Table 30. Evacuation Time and Survival Rate in Multiplayer Mode

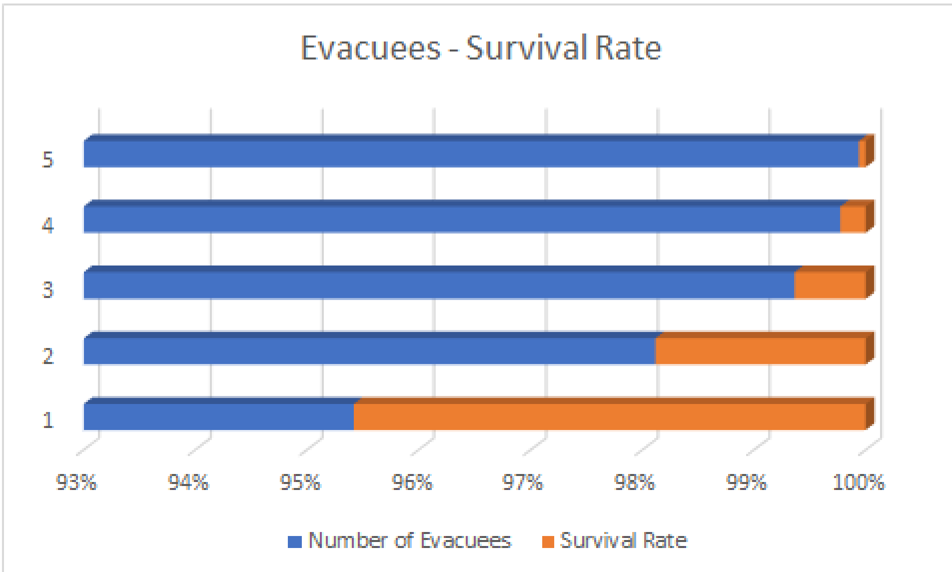


Figure 56. Evacuees and Survival Rate Correlation

The last pointer indicates if the user learned to navigate through the ship and eventually if they were trained to safely evacuate a ship, which is the main question of this work.

Evacuation Scenario	**Time (minutes)**	**Survival Rate**	**Number of Human Evacuees(n_h)**	**Number of Bot Evacuees (n_b)**	**Instigator**
1(m)a	15	45%	6	214	Fire
1(m)b	15	51%	6	214	Fire
1(m)c	15	50%	6	214	Fire & Smoke
1(m)d	15	69%	6	214	Fire & Smoke
1(m)e	15	71%	6	314	Fire, Smoke, Poisonous Gases, Rough Sea

Table 31. Impact of Training on Evacuation Performance

6.4.1 Gamification & Edutainment

After every session, the testers were asked to answer some questions to assess their immersion. In most scenarios, the users stated that they were fully immersed after the first few minutes of the game, due to the intense antagonistic and survival essence of the simulation. The use of headphones materialized the full immersion faster by far, as the users were immersed before the first two minutes. After the fourth session, some users declared that they found it difficult to be fully immersed in the virtual world and one stated that they could not immerse at all. This phenomenon is discussed in the General Results and Discussion below.

Evacuation Scenario	Full Immersion	Immersion (average time in m)	Successfully Evacuated	Injured
1	100%	3	66%	50%
2	100%	3	66%	50%
3	100%	5	83%	50%
4	100%	6	83%	33%
5	83%	7	100%	33%

Table 32. Human Players Testing and Immersion

6.5 General Results & Discussion

In this subchapter the results are divided into three categories. The assessment of the Game Engines as developing tools, the evaluation of the SES as a Serious Game/Simulator and the validation of the results.

6.5.1 Game Engines as Developing Tools

The Game Engines and more specifically Unreal Engine 4 have been proven a tool capable of developing reliable Evacuation Serious Games. Unreal Engine 4 can model phenomena and elements of evacuation, such as human behavior and movement, as well as spatial phenomena such as congestion and bottlenecks, using its own tools and external models. A Graphical Environment is provided to set up realistic evacuation structures and evacuation scenarios with a highly adjustable physics engine that simulates credibly the law of physics, into the virtual world. The Unreal Engine (and Unity) Physics Engines rarely failed to meet the requirements of a realistic environment and simulated all the physical laws reliably without any significant issues. Important tools such as Controls, Camera manipulation, Character development, and AI systems are provided, coupled with the support of a programming language (C++) and block scripting language (Blueprints). A serious game or a simulator usually includes multiple models for the representation of the structures, the objects, and the people in the evacuation area. UE4 handles the external models effectively with low importation time and rare distortions. The models of Express Samina were imported without significant delays or the introduction of anomalies, and the models of the objects were imported even easier and in much shorter times. As for the characters, their importation encountered no issues and all of them kept their features, characteristics, materials, skins, rigs, and animation properties. The hazardous elements (fire, smoke, etc.) are easily created as Blueprints that hold multiple properties and colliders, while they can be spawned by a simple click. They are also incorporated into the virtual environment relatively easily and can be attached to functionalities through coding. The lighting conditions are implemented easily with a variety of light types (Directional, Spot, Point, Rect, and Sky Light) allowing the application of realistic and changeable lighting conditions, such as the ship's interior illumination and the day/night rotation. Multiplayer and networking are also implemented, and multiple users can select between different types of avatar, while the application can control a high number of bots, which surpasses 2000 (n>2000). The implementation of the multiplayer component requires expertise in UE4 Blueprint or C++ development. Conclusively, Unreal Engine 4 has been proven a reliable development framework for Evacuation Serious Games, with multiplayer, AI, modeling, and a realistic 3d graphical environment, accompanied by a powerful physics engine.

6.5.2 Ship Evacuation Simulator (SES)

A 3D evacuation model like SES, incorporates more human interaction factors than 2D models. Moreover, human users may actively participate as evacuees. A 3D ES is capable of implementing Spatial and Behavioral phenomena, with the same capacity of a 2D one, extending its capabilities to include more realistic environments. In a 3D environment, elements such as listing, falling objects, fog, etc can also be applied and reviewed in runtime. Two shortcomings of 3D ES could be the complicated setup and the limited repeatability, compared to a 2D one, as the evacuation sessions may last longer. SES collects the simulated data and the evacuation scenarios can be monitored providing spatial information. The collected data can be stored and analyzed later. While it is really challenging to find a large number of testers, SES gives the ability to properly simulate an evacuation scenario with only a small number of users-testers along with several bots while the conditions and the motion of the crowd remain accurate. Towards this direction, future research could assess the optimum human users/bots' analogy, toward the maximum simulation reliability.

The main goal of training the evacuees, keeping their interest intact, was achieved as the users were fully immersed to the virtual world (83% - 100% for 3 to 7 minutes) and they got more familiar with the virtual world after every evacuation session, which is proven by their improved performance in every session. The results of first-time testers were worse than the ones after 3 or 4 sessions, even with more challenging scenarios (decreased allowed time, more evacuees, more hazardous elements). In Fig. XX, we can see that the survival rate of 45% in the first session with Fire only, was increased to 71% after 5 sessions, although in the final scenario Smoke, Poisonous Gases, and Rough Sea had been introduced. The same stands for the user's immersion with the exception that as noted before, the users tend to lose focus after 7 minutes on average. Therefore, the assumption is that the users have been trained after repeating the simulations several times, but the full immersion time is limited. The different evacuee's types behaved as expected and their results were validated when compared to previous observations and evacuation incidents. Adult evacuees have a lower casualty rate because of their higher speed, stamina, and size, a fact indicated in Table 29, where the Adult type evacuees casualties rate varies from 13% to 26% of the total evacuees, while the corresponding Old ones have a rate from 38% to 62% and the Teen ones with a rate from 36% to 25%. The only shortcoming of adult evacuees is that they may get stuck easily into or next to congested areas due to their large size and speed, which makes them prone to congestion in narrow areas. Teen evacuees are slower, but because of their smaller size can fit into smaller spaces and avoid being stuck in large congestions. Their small size, though, decreases their speed and maybe pushed easier over by larger evacuees and/or objects. Teen evacuees have the second-worst casualty rate, after the Old evacuees. The Old evacuees have the lowest speed and stamina and thus they have the highest casualties. These results verify what we already know about evacuees of different ages as explained herein and in the previous chapters. The spatial phenomena appeared as expected and it was observed that when the number of evacuees has reduced the congestion, bottlenecks and even the counterflow were reduced proportionally.

6.5.3 Experimental Data

Moreover, during all the evacuation scenarios, most of the bots behaved, as expected, waiting until the initial response time expired, detecting all the hazardous elements into their field of view or hearing range, finding exits, and following the closest clear paths toward them. The bots attempted to stay away from any sources of fire and smoke and the fatalities are attributed to trapped evacuees or evacuees that could not escape in time. The bots created arches and bottlenecks in front of narrow corridors and doors when many them attempted to cross the area. When many evacuees were gathered to the same area, Congestion was applied, reducing the speed of the evacuees near the affected area. When the bots' speed remained low for more than 5 seconds, due to congestion or other spatial phenomena, the Dynamic Rerouting was activated, searching for alternative routes, as has been observed in real evacuation incidents. Ascending the stairs slowed down the evacuees and the crowds, as expected while descending increased the evacuation speed. The data was validated with data from the Express Samina disaster, models, and various real incidents. Therefore, we conclude that the AI-controlled bots used in SES can imitate the movement and behavior of human evacuees, to a high degree and in most cases.

Runtime "unexpected" events have significantly affected the outcome and output of all the evacuation scenarios. Runtime events resulted in increased casualties' ratios, an increased overall evacuation time, and a higher probability of trapped or isolated evacuees. Furthermore, SES incorporates gamification qualities that seem to successfully immerse the human users into the simulated environment, pursuing clear, reachable, and understandable goals, interacting with human-like bots-evacuees, and developing a competitive environment among the participants. More specifically, Gamification and user participation are discussed herein. The Gamification and Edutainment elements seem to impact the overall process as shown in the results, as the users struggle to compete with others and improve their performance with every run, while they are chasing their goals. The users improved their performance every time they played as they were familiarized with the environment and tried to find ways to better themselves and gradually to help other evacuees. The last observation started to appear after the first evacuation session. The users felt more confident in their skills and more familiar with the structure and attempted to help others, stalling, and even broadcasting messages to the users close to them. This caused some unnecessary casualties but helping others during an evacuation is a common practice during evacuations and therefore it was considered as a contribution to the realism of the application. The shortcoming of this phenomenon is that experienced gamers could easily work around the system and after a few sessions demonstrated advanced proficiency, which is not what we expect to observe in a real evacuation egress. Because of this, the users should be avoided, and a tester-user should be ideally asked to participate in up to three evacuation sessions. In contrast, that is another proof of the benefits of evacuee training, as this knowledge and confidence could be used during a real evacuation incident. For the roles of the evacuees, experienced gamers, with more than 10 years of gaming experience in Action, Shoot-et-up, and RPG games, were selected to avoid distortions due to lack of gaming skills. The users were immersed in most of the cases after the first two to three minutes. After the second session, the users started to lose focus and some users declared that they found it difficult to focus, due to the repeatability and trivial nature of the game. In the first scenario the immersion was 100% after 3 minutes on average, in the third scenario it was 100%, but after 5 minutes on average, while in the last (6th) session it was 83% in 7 minutes on average (more than half the length of the scenario). This concludes that the testers of ES should take long breaks and disengage before they play more than two evacuation sessions in a row, to improve their ability to immerse themselves. In contrast, the performance of the evacuees was proportionally increased, as they were repeatedly participating in the scenarios. For the first two scenarios, the evacuation success was 66%, which was increased to 83% for the third and fourth scenario and to 100% for the fifth, even if the difficulty was increased. This is attributed to the human nature of adaptivity and learning from past experiences. In fact, the testers memorized the best routes and followed them despite the extra hardships. Therefore, the testers should be switched to different scenarios or take long breaks to ensure the integrity of the testing. Moreover, the number of injured evacuees decreased as the testers learned how to avoid and evade hazardous spots and elements, after a few runs. The number of injured evacuees is 50% for the first three sessions and drops to 33% for the last two. This result indicated that ES can be used for passengers and crew training to decrease the casualties by training them to avoid dangerous spots during an evacuation. The results prove that the human users can play the role of evacuees as their results are similar to the ones of the computer-controlled bots in the Simulation-only sessions, though slightly improved. The users were immersed in the virtual environment and participated as real evacuees. As the number of users was increased from one to six the evacuation approximated the realism and the outcomes of a real-world evacuation, especially when the total number of evacuees remained low. SES could also be used as a prototype for evacuation or crew training.

Future works intend to use the proposed simulator as a testbed for HRI research. Furthermore, SES is expected to include a new crewmember/rescue-team member mode and the automatic spreading ability for elements such as smoke, fire, and gas as well as water inlet. The implementation of seasickness is also considered as an addition to the bots and human players in future releases. A communication system that will allow communication from evacuees-bot and bots-bots is an upcoming feature. Later releases of the SES are planned to include Machine Learning for the bots, to learn from their experience and act accordingly. Another major addition will be the implementation of multiple ship categories and types, extending its use to types other than Passenger Ships. Although SES is considered a robust simulator comparing previous works in the field (Ginnis et al., 2015; Stefanidis et al., 2019), the credibility of the results presented here are going to be further enhanced with the implementation of the above-mentioned features and the conduction of simulations, which involve large numbers of human players and bots. A final consideration would be the implementations of these features in the new Unreal Engine 5, for improved physics system and graphics.

6.6 SUMMARY

SES is a 3D Serious Game with elements of Simulation facilitating the impersonation of evacuees by computer-controlled autonomous bots that perform a risk assessment and continuously calculate route conditions (through a pathfinding algorithm), affect neighboring occupants, determine bottleneck points, and select the best evacuation routes.

This Serious Game collects data of the evacuation scenarios and enables users to observe and evaluate the course of a scenario, giving them the ability to mix up human users and computer-controlled bots. It also allows us to assess the impact on the reliability of the results of the evacuation scenarios, if AI-controlled bots can act as human beings should have acted, and to what degree and how runtime events (fire, fog, etc.) could alter the course of an evacuation scenario. Based on the experimental results, the conclusion is that the users can be trained to evacuation safety standards, improving their survivability during an urgent evacuation, if they keep their immersion at high levels.

Ships have become larger in scale and function, and occasionally their complexity has increased considerably. This brings up many difficulties in evacuation and rescue when an emergency occurs. Therefore, effective evacuation and risk methods should be predicted and applied to design, safety training, and education. SES is a lightweight simulator with simultaneous participation of human users and computer-controlled bots as evacuees in gamified multiplayer scenarios by the runtime spawning of 3D elements such as fire and smoke. Realistic and valid results can be obtained by applying SES in evacuation simulation and it has several benefits such as flexible technology and economic feasibility. The results were validated compared to data from real evacuation and experimental data. SES can be used to test the safety of passenger ships and train evacuees or personnel.

References

1. Addis, M. (2005). New technologies and cultural consumption–edutainment is born!. *european Journal of marketing*.
2. Almeida, J. E., Rossetti, R. J., & Coelho, A. L. (2013). Crowd simulation modeling applied to emergency and evacuation simulations using multi-agent systems. *arXiv preprint arXiv:1303.4692*.
3. Alvarez, J., & Djaouti, D. (2011). An introduction to Serious game Definitions and concepts. *Serious Games & Simulation for Risks Management*, *11*(1), 11-15.
4. Amirafshari, P., Barltrop, N., Bharadwaj, U., Wright, M., & Oterkus, S. (2018). A review of nondestructive examination methods for new-building ships undergoing classification society survey. Journal of Ship Production and Design, 34(1), 9-19.
5. Anderson, E. F., Engel, S., Comninos, P., & McLoughlin, L. (2008, November). The case for research in game engine architecture. In *Proceedings of the 2008 Conference on Future Play: Research, Play, Share* (pp. 228-231).
6. Aksakal, N. (2015). Theoretical view to the approach of the edutainment. *Procedia-Social and Behavioral Sciences*, *186*, 1232-1239.
7. Autodesk, (2020). Autodesk 3D Studio Max Learning Center. https://help.autodesk.com/view/3DSMAX/2020/ENU/
8. Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *JOSA A*, *5*(12), 2210-2219.
9. Banks, J. (1999, December). Introduction to simulation. In *Proceedings of the 31st conference on Winter simulation: Simulation---a bridge to the future-Volume 1* (pp. 7-13).
10. Barcroft, H., & Edholm, O. G. (1943). The effect of temperature on blood flow and deep temperature in the human forearm. *The Journal of physiology*, *102*(1), 5-20.
11. Barregard, L., Sällsten, G., Gustafson, P., Andersson, L., Johansson, L., Basu, S., & Stigendal, L. (2006). Experimental exposure to wood-smoke particles in healthy humans: effects on markers of inflammation, coagulation, and lipid peroxidation. *Inhalation toxicology*, *18*(11), 845-853.
12. Benthorn, L., & Frantzich, H. (1996). Fire alarm in a public building: How do people evaluate information and choose evacuation exit?. *LUTVDG/TVBB--3082--SE*.
13. Benthorn, L., & Frantzich, H. (1999). Fire alarm in a public building: How do people evaluate information and choose an evacuation exit?. *Fire and Materials*, *23*(6), 311-315.
14. Bernardini, G., Quagliarini, E., & D'Orazio, M. (2016). Towards creating a combined database for earthquake pedestrians' evacuation models. *Safety science*, *82*, 77-94.
15. Bernardini, G. (2015). An agent-based simulation model for earthquake pedestrians' evacuation in historical urban fabric. *Tema: Technology, Engineering, Materials and Architecture*, *1*(1), 1-6.
16. Bishop, L., Eberly, D., Whitted, T., Finch, M., & Shantz, M. (1998). Designing a PC game engine. *IEEE Computer Graphics and Applications*, *18*(1), 46-53.
17. Blake, S., Galea, E., Westang, H., & Dixon, A. (2004). An analysis of human behaviour during the WTC disaster of 9/11 based on published survivor accounts.
18. Blix, E., Bye, R., Kleiven, E., Almklov, P., Kongsvik, T., Gåseidnes, H., & Berntsen, V. (2015). What is a ship? Ship categories and application of AIS data and accident

statistics for the normalization of ship risk. *Safety and Reliability of Complex Engineered Systems*, 315-322.

19. Bo, Y., Cheng, W., Hua, H., & Lijun, L. (2007, December). A multi-agent and PSO based simulation for human behavior in emergency evacuation. In *Computational Intelligence and Security, 2007 International Conference on* (pp. 296-300).
20. Boulougouris, E., & Papanikolaou, A. (2002). Modeling and simulation of the evacuation process of passenger ships. Paper presented at the Proceedings of the 10th international congress of the international maritime association of the Mediterranean, Crete, Greece.
21. Bratley, P., Fox, B. L., & Schrage, L. E. (2011). *A guide to simulation*. Springer Science & Business Media.
22. Broughton, E. (2005). The Bhopal disaster and its aftermath: a review. *Environmental Health*, *4*(1), 1-6.
23. Brown, E., & Cairns, P. (2004, April). A grounded investigation of game immersion. In *CHI'04 extended abstracts on Human factors in computing systems* (pp. 1297-1300).
24. Bryan, J. L. (1999). Human behaviour in fire: the development and maturity of a scholarly study area. *Fire and Materials, 23*(6), 249-253.
25. Cassuto, J., & Tarnow, P. (2003). The discotheque fire in Gothenburg 1998: A tragedy among teenagers. *Burns*, *29*(5), 405-416.
26. Charsky, D. (2010). From edutainment to serious games: A change in the use of game characteristics. *Games and culture*, *5*(2), 177-198.
27. Chen, J., Wang, J., Wang, B., Liu, R., & Wang, Q. (2018). An experimental study of visibility effect on evacuation speed on stairs. *Fire safety journal*, *96*, 189-202.
28. Chen, J. J., Wang, X. G., & Fang, Z. (2016). Collaborative Evacuation Strategy of Ultra-tall Towers among Stairs and Elevators. Procedia Engineering, 135, 169-173.
29. Chen, C. C., & Aggarwal, J. K. (2009, December). Recognizing human action from a far field of view. In *2009 Workshop on Motion and Video Computing (WMVC)* (pp. 1-7). IEEE.
30. Choukroun, M. L., Kays, C., & Varène, P. (1989). Effects of water temperature on pulmonary volumes in immersed human subjects. *Respiration physiology*, *75*(3), 255-265.
31. Chu, J. C., Chen, A. Y., & Lin, Y. F. (2017). Variable guidance for pedestrian evacuation considering congestion, hazard, and compliance behavior. *Transportation Research Part C: Emerging Technologies*, *85*, 664-683.
32. Chu, M. L., Parigi, P., Law, K., & Latombe, J. C. (2014). Modeling social behaviors in an evacuation simulator. *Computer Animation and Virtual Worlds*, *25*(3-4), 373-382.
33. Chiewchengchol, W., Koga, T., & Hirate, K. (2011). Development of an evacuation simulator using a walkthrough system and research on evacuation behavior in the case of fire. *Journal of Asian Architecture and Building Engineering*, *10*(1), 101-108.
34. Chunmiao, Y., Chang, L., Gang, L., & Peihong, Z. (2012). Safety evacuation in building engineering design by using BuildingExodus. *Systems Engineering Procedia*, *5*, 87-92.
35. Cłapa, I., Cisek, M., Tofiło, P., & Dziubiński, M. (2015). Firefighters ascending and evacuation speeds during counter flow on staircase. *Safety science*, *78*, 35-40.
36. Cohn, P. J., Carroll, M. S., & Kumagai, Y. (2006). Evacuation behavior during wildfires: results of three case studies. *Western Journal of Applied Forestry*, *21*(1), 39-48.
37. Collins, B. L., Dahir, M. S., & Madrzykowski, D. (1990). *Evaluation of exit signs in clear and smoke conditions*. Gaithersburg, MD: National Institute of Standards and Technology.

38. Collins, B. L., Dahir, M. S., & Madrzykowski, D. (1992). Visibility of exit signs in clear and smoky conditions. *Journal of the Illuminating Engineering Society*, *21*(1), 69-84.
39. Costella, J. P. (1995). A Beginner's Guide to the Human Field of View. *School of Physics, The University of Melbourne*.
40. CryEngine Documentation page, https://docs.cryengine.com/.
41. Couasnon, P., de Magnienville, Q., Wang, T., & Claramunt, C. (2019). *A Multi-agent System for the Simulation of Ship Evacuation.* Paper presented at the International Symposium on Web and Wireless Geographical Information Systems.
42. Dhaya, R. (2020). Improved Image Processing Techniques for User Immersion Problem Alleviation in Virtual Reality Environments. *Journal of Innovative Image Processing (JIIP)*, *2*(02), 77-84.
43. De Paolis, L. T., Aloisio, G., Celentano, M. G., Oliva, L., & Vecchio, P. (2011, March). MediaEvo project: a serious game for edutainment. In *2011 3rd International Conference on Computer Research and Development* (Vol. 4, pp. 524-529). IEEE.
44. De Paolis, L. T., Celentano, M. G., Oliva, L., Vecchio, P., & Aloisio, G. I. O. V. A. N. N. I. (2011, March). MediaEvo project: The life in a medieval town. In *10th WSEAS international conference on communications, electrical & computer engineering, and 9th WSEAS international conference on Applied electromagnetics, wireless and optical communications* (pp. 22-27).
45. DePaolis, L. T., Aloisio, G., & Manco, M. (2011, February). Navigation and interaction in the virtual reconstruction of the town of Otranto in the middle ages. In *The 4th International Conference on Advances in Computer-Human Interactions (ACHI 2011)* (pp. 120-124).
46. De Paolis, L. T., Aloisio, G., Celentano, M. G., Oliva, L., & Vecchio, P. (2009, September). Design and development of a virtual reality application for edutainment in cultural heritage. In *2009 15th International Conference on Virtual Systems and Multimedia* (pp. 80-84). IEEE.
47. Deterding, S., Dixon, D., Khaled, R., & Nacke, L. (2011, September). From game design elements to gamefulness: defining" gamification". In *Proceedings of the 15th international academic MindTrek conference: Envisioning future media environments* (pp. 9-15).
48. Deterding, S. (2012). Gamification: designing for motivation. *interactions, 19*(4), 14-17.
49. De Vries, J. V. (n.d.). *Learn OpenGL*. LearnOpenGL. https://learnopengl.com/
50. Dickie, J. F. (1995). Major crowd catastrophes. *Safety science*, *18*(4), 309-320.
51. Dickson, P. E., Block, J. E., Echevarria, G. N., & Keenan, K. C. (2017, June). An experience-based comparison of unity and unreal for a stand-alone 3D game development course. In *Proceedings of the 2017 ACM Conference on Innovation and Technology in Computer Science Education* (pp. 70-75).
52. Ding, Y., Yang, L., Weng, F., Fu, Z., & Rao, P. (2015). Investigation of combined stairs elevators evacuation strategies for high rise buildings based on simulation. *Simulation Modelling Practice and Theory*, *53*, 60-73.
53. Ding, N., & Sun, C. (2020). Experimental study of leader-and-follower behaviours during emergency evacuation. *Fire safety journal*, *117*, 103189.
54. Dou, Z., Mebarki, A., Cheng, Y., Zheng, X., Jiang, J., Wang, Y., ... & Li, J. (2019). Review on the emergency evacuation in chemicals-concentrated areas. *Journal of Loss Prevention in the Process Industries*, *60*, 35-45.

55. Dubbels, B. (2013). Gamification, serious games, ludic simulation, and other contentious categories. *International Journal of Gaming and Computer-Mediated Simulations (IJGCMS)*, *5*(2), 1-19.
56. Duncan, S. J., Schofield, G., Duncan, E. K., & Hinckson, E. A. (2007). Effects of age, walking speed, and body composition on pedometer accuracy in children. *Research quarterly for exercise and sport, 78*(5), 420-428.
57. Fahy, R. F., & Proulx, G. (1997). Human behavior in the world trade center evacuation. *Fire Safety Science*, *5*, 713-724. Fire Safety Science Digital Archive.
58. Eberly, D. (2006). *3D game engine design: a practical approach to real-time computer graphics*. CRC Press.
59. Egenfeldt-Nielsen, S. (2011). *Beyond edutainment: Exploring the educational potential of computer games*. Lulu. com.
60. Enoka, R. M., & Duchateau, J. (2016). Translating fatigue to human performance. *Medicine and science in sports and exercise*, *48*(11), 2228.
61. Ermi, L., & Mäyrä, F. (2005). Fundamental components of the gameplay experience: Analysing immersion. *Worlds in play: International perspectives on digital games research*, *37*(2), 37-53.
62. Fridolf, K., Ronchi, E., Nilsson, D., & Frantzich, H. (2015). The relationship between obstructed and unobstructed walking speed: Results from an evacuation experiment in a smoke filled tunnel. In *International symposium on Human Behaviour in Fire, 2015* (pp. 537-548). Interscience Communications.
63. Gaillard, A. W. (2001). *Stress, workload, and fatigue as three biobehavioral states: a general overview*. Lawrence Erlbaum Associates Publishers.
64. Gatsou, M., Gray, L., & Niininen, O. (2005). Crisis Management For Tourism–A Case Study Of The Greek Passenger Shipping Industry. *La Trobe University*.
65. Gershon, R. R., Qureshi, K. A., Rubin, M. S., & Raveis, V. H. (2007). Factors associated with high-rise evacuation: qualitative results from the World Trade Center Evacuation Study. *Prehospital and disaster medicine*, *22*(3), 165.
66. Giakoumatos, S. D., & Kalogirou, E. N. (2020). "Sea Diamond" Wreckage—12 Years after the Fatal Maritime Accident, the Vessel Remains an Environmental Concern. *Open Journal of Ecology*, *10*(08), 537.
67. Ginnis, A. I., Kostas, K. V., Politis, C. G., & Kaklis, P. D. (2010). VELOS: A VR platform for ship-evacuation analysis. *Computer-Aided Design*, *42*(11), 1045-1058.
68. Ginnis, A. I., Kostas, K. V., Politis, C. G., & Kaklis, P. D. (2015). VELOS-A VR environment for ship applications: current status and planned extensions. In *Virtual realities* (pp. 33-55): Springer.
69. Giustiniano, L., e Cunha, M. P., & Clegg, S. (2016). The dark side of organizational improvisation: Lessons from the sinking of Costa Concordia. *Business Horizons*, *59*(2), 223-232.
70. Goulielmos, A. M., Goulielmos, M. A., & Gatzoli, A. (2009). The accident of passenger‐car vessel Samina Express (2000), when 80 persons died. *Disaster Prevention and Management: An International Journal*.
71. Gregory, J. (2018). *Game engine architecture*. crc Press.

72. Guarin, L., Majumder, J., Shigunov, V., Vassalos, G., & Vassalos, D. (2004). Fire and flooding risk assessment in ship design for ease of evacuation. Paper presented at the 2nd International Conference on Design for Safety, Osaka, Japan.
73. Gwynne, S., Galea, E. R., Lawrence, P. J., Owen, M., & Filippidis, L. (2000). Adaptive decision-making in building EXODUS in response to exit congestion. *Fire Safety Science*, *6*, 1041-1052.
74. Gwynne, S., Galea, E. R., Lawrence, P. J., & Filippidis, L. (2001). Modelling occupant interaction with fire conditions using the buildingEXODUS evacuation model. *Fire Safety Journal*, *36*(4), 327-357.
75. Gwynne, S. M., Boyce, K. E., Kuligowski, E. D., Nilsson, D., Robbins, A., & Lovreglio, R. (2016). Pros and cons of egress drills. *Interflam 2016*, 1657-1670.
76. Hamari, J., Koivisto, J., & Sarsa, H. (2014, January). Does gamification work?--a literature review of empirical studies on gamification. In *2014 47th Hawaii international conference on system sciences* (pp. 3025-3034). Ieee.
77. Harth, J., Hofmann, A., Karst, M., Kempf, D., Ostertag, A., Przemus, I., & Schaefermeyer, B. (2018). Different types of users, different types of immersion: A user study of interaction design and immersion in consumer virtual reality. *IEEE Consumer Electronics Magazine*, *7*(4), 36-43.
78. Harrison, C. Passenger behaviour in aircraft emergencies (pp. 19-24).
79. Ha, S., Ku, N. K., Roh, M. I., & Lee, K. Y. (2012). Cell-based evacuation simulation considering human behavior in a passenger ship. *Ocean engineering*, *53*, 138-152.
80. Helbing, D., Farkas, I. J., Molnar, P., & Vicsek, T. (2002). Simulation of pedestrian crowds in normal and evacuation situations. *Pedestrian and evacuation dynamics*, *21*(2), 21-58.
81. Helbing, D. (2012). Social Self-Organization. Understanding Complex Systems. *Berlin: Springer-Verlang. DOI, 10*, 978-973
82. Helbing, D., & Mukerji, P. (2012). Crowd disasters as systemic failures: analysis of the Love Parade disaster. *EPJ Data Science*, *1*(1), 1-40.
83. Heliövaara, S., Korhonen, T., Hostikka, S., & Ehtamo, H. (2012). Counterflow model for agent-based simulation of crowd dynamics. *Building and Environment*, *48*, 89-100.
84. Herndon, D. N., & Spies, M. (2001, February). Modern burn care. In *Seminars in pediatric surgery* (Vol. 10, No. 1, pp. 28-31). WB Saunders.
85. Himann, J., Cunningham, D., Rechnitzer, P., & Paterson, D. (1988). Age-related changes in speed of walking. *Medicine and science in sports and exercise, 20*(2), 161.
86. Hofinger, G., Zinke, R., & Künzer, L. (2014). Human factors in evacuation simulation, planning, and guidance. *Transportation Research Procedia*, *2*, 603-611.
87. Horii, H., Ito, A., TSUJIUCHI, N., Fukuda, T. A. K. A. H. I. R. O., & Kasahara, Y. U. S. U. K. E. (2019). Fundamental study of an adaptive evacuation guide sign by using a discrete element method-based simulation. *WIT Transactions on Engineering Sciences*, *125*, 143-150.
88. Hoskins, B. L., & Milke, J. A. (2012). Differences in measurement methods for travel distance and area for estimates of occupant speed on stairs. *Fire Safety Journal*, *48*, 49-57.
89. Houts, P. S., Lindell, M. K., Hu, T. W., Cleary, P. D., Tokuhata, G., & Flynn, C. B. (1984). Protective action decision model applied to evacuation during the three mile island crisis. *International Journal of Mass Emergencies and Disasters*, *2*(1), 27-39.
90. Hou, L., Liu, J. G., Pan, X., & Wang, B. H. (2014). A social force evacuation model with the leadership effect. *Physica A: Statistical Mechanics and its Applications*, *400*, 93-99.

91. Howells, R. (1999). A Brief History of the Titanic. In *The Myth of the Titanic* (pp. 13-36). Palgrave Macmillan UK.
92. Hu, W., Qu, Z., & Zhang, X. (2012, June). A new approach of mechanics simulation based on game engine. In *2012 Fifth International Joint Conference on Computational Sciences and Optimization* (pp. 619-622). IEEE.
93. Hu, M., Cai, W., & Zhao, H. (2019). Simulation of Passenger Evacuation Process in Cruise Ships Based on A Multi-Grid Model. Symmetry, 11(9), 1166.
94. Huo, F., Song, W., Chen, L., Liu, C., & Liew, K. M. (2016). Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building. *Safety science*, *86*, 165-173.
95. Huotari, K., & Hamari, J. (2012, October). Defining gamification: a service marketing perspective. In *Proceeding of the 16th international academic MindTrek conference* (pp. 17-22).
96. Huotari, K., & Hamari, J. (2017). A definition for gamification: anchoring gamification in the service marketing literature. *Electronic Markets*, *27*(1), 21-31.
97. IJsselsteijn, W., De Kort, Y., Poels, K., Jurgelionis, A., & Bellotti, F. (2007, June). Characterizing and measuring user experiences in digital games. In *International conference on advances in computer entertainment technology* (Vol. 2, p. 27).
98. Ibrahim, A. M., Venkat, I., & De Wilde, P. (2017). Uncertainty in a spatial evacuation model. *Physica A: Statistical Mechanics and its Applications*, *479*, 485-497.
99. IJsselsteijn, W., De Kort, Y., Poels, K., Jurgelionis, A., & Bellotti, F. (2007, June). Characterising and measuring user experiences in digital games. In *International conference on advances in computer entertainment technology* (Vol. 2, p. 27).
100. IMO (October, 2020). IMO. www.imo.org
101. Ingalls, R. G. (2011, December). Introduction to simulation. In *Proceedings of the 2011 Winter Simulation Conference (WSC)* (pp. 1374-1388). IEEE.
102. Irawati, S., Hong, S., Kim, J., & Ko, H. (2008, December). 3D edutainment environment: learning physics through VR/AR experiences. In *Proceedings of the 2008 International Conference on Advances in Computer Entertainment Technology* (pp. 21-24).
103. Jain, L. C. (2011). *Serious games and edutainment applications* (Vol. 504). M. Ma, & A. Oikonomou (Eds.). London: Springer.
104. Jasionowski, A., & Vassalos, D. (2011). New Insights on the Sinking of MV Estonia. In *Contemporary Ideas on Ship Stability and Capsizing in Waves* (pp. 827-839). Springer Netherlands.
105. Jeon, G. Y., Na, W. J., Hong, W. H., & Lee, J. K. (2019). Influence of design and installation of emergency exit signs on evacuation speed. *Journal of Asian Architecture and Building Engineering*, *18*(2), 104-111.
106. Jianfeng, L., Bin, Z., Yang, W., & Mao, L. (2009). The unfolding of the '12.23'Kaixian blowout accident in China. *Safety science*, *47*(8), 1107-1117.
107. Ji, Q., & Gao, C. (2006). Simulating crowd evacuation with a leader-follower model. *IJCSES*, *1*(4), 249-252.
108. Jin, T., & Yamada, T. (1985). Irritating effects of fire smoke on visibility. *Fire Science and Technology*, *5*(1), 79-90.
109. Johnson, C. W. (2006). Using computer simulations to support a risk-based approach for hospital evacuation. *A Department of Computing Science Briefing*.

110. Johnson, W. L. (2007). Serious use of a serious game for language learning. *Frontiers in Artificial Intelligence and Applications*, *158*, 67.
111. Joo, J., Kim, N., Wysk, R. A., Rothrock, L., Son, Y. J., Oh, Y. G., & Lee, S. (2013). Agent-based simulation of affordance-based human behaviors in emergency evacuation. *Simulation Modelling Practice and Theory*, *32*, 99-115.
112. Keating, J. P. (1982). The myth of panic. Fire Journal, 76(3), 57-61.
113. Kerfoot, B. P., & Kissane, N. (2014). The use of gamification to boost residents' engagement in simulation training. *JAMA surgery*, *149*(11), 1208-1209.
114. Kessenich, J., Sellers G., Shreiner, D. (2016). OpenGL Programming Guide: The Official Guide to Learning OpenGL, Version 4.5 with SPIR-V
115. Kim, H., Park, J.-H., Lee, D., & Yang, Y.-s. (2004). Establishing the methodologies for human evacuation simulation in marine accidents. Computers & Industrial Engineering, 46(4), 725-740.
116. Kinateder, M., Ronchi, E., Nilsson, D., Kobes, M., Müller, M., Pauli, P., & Mühlberger, A. (2014, September). Virtual reality for fire evacuation research. In *2014 federated conference on computer science and information systems* (pp. 313-321). IEEE.
117. Kinateder, M., Warren, W. H., & Schloss, K. B. (2019). What color are emergency exit signs? Egress behavior differs from verbal report. *Applied ergonomics*, *75*, 155-160.
118. Kluepfel, H. L. (2003). *A cellular automaton model for crowd movement and egress simulation* (Doctoral dissertation, Universität Duisburg-Essen, Fakultät für Physik).
119. Kobes, M., Helsloot, I., de Vries, B., Post, J. G., Oberijé, N., & Groenewegen, K. (2010). Wayfinding during fire evacuation; an analysis of unannounced fire drills in a hotel at night. *Building and Environment*, *45*(3), 537-548.
120. Kostas, K. V., Ginnis, A. I., Politis, C. G., & Kaklis, P. (2011, September). Use of VELOS platform for modeling and assessing crew assistance and passenger grouping in ship-evacuation analysis. In *Conference of the International Maritime Association of Mediterranean IMAM 2011* (pp. 729-737).
121. Kostas, K. V., Ginnis, A. A., Politis, C. G., & Kaklis, P. D. (2014, June). VELOS: Crowd Modeling for Enhanced Ship Evacuation Analysis. In *International Conference on Virtual, Augmented and Mixed Reality* (pp. 402-413). Springer, Cham.
122. Kholshchevnikov, V. V., Samoshin, D. A., Parfyonenko, A. P., & Belosokhov, I. P. (2012). Study of children evacuation from pre‐school education institutions. *Fire and Materials*, *36*(5-6), 349-366.
123. Kholshevnikov, V. V., Samoshin, D. A., & Parfenenko, A. P. (2009). Pre-school and school children building evacuation. *State Moscow University of Civil Engineering, Academy of State Fire Service of Russia, Moscow, Russia*.
124. Klüpfel, H., Meyer-König, T., Wahle, J., & Schreckenberg, M. (2001). Microscopic simulation of evacuation processes on passenger ships. In *Theory and practical issues on cellular automata* (pp. 63-71). Springer, London.
125. Klüpfel, H., & Meyer-König, T. (2005). Simulation of the Evacuation of a football stadium using the CA Model PedGo. In *Traffic and granular flow'03* (pp. 423-428). Springer, Berlin, Heidelberg.
126. Klüpfel, H., & Meyer-König, T. (2014). PedGo Guardian: Evacuation Decision Support System for Events. In *Pedestrian and Evacuation Dynamics 2012* (pp. 445-454). Springer, Cham.

127. Koo, J., Kim, B. I., & Kim, Y. S. (2014). Estimating the effects of mental disorientation and physical fatigue in a semi-panic evacuation. *Expert Systems with Applications*, *41*(5), 2379-2390.
128. Korhonen, T., Hostikka, S., Heliövaara, S., & Ehtamo, H. (2010). FDS+ Evac: an agent based fire evacuation model. In *Pedestrian and Evacuation Dynamics 2008* (pp. 109-120). Springer, Berlin, Heidelberg.
129. Kougioumtzoglou, G. &Lepouras, G. (2021). Computerized Simulators for the Marine Industry, the case study of SES, a game-engine-based environment. CHI Greece 2021 Conference (https://chigreece.gr/2021/programme/list-of-papers/33/).
130. Kougioumtzoglou, G., Theodoropoulos, A., & Lepouras, G. (2021). A Guide for the Development of Game-Based Evacuation Simulators. In *Educating Engineers for Future Industrial Revolutions: Proceedings of the 23rd International Conference on Interactive Collaborative Learning (ICL2020), Volume 1 23* (pp. 554-566). Springer International Publishing.
131. Kougioumtzoglou, G., Theodoropoulos, A., & Lepouras, G. (2021). Design and development of a game-engine based simulator specialized on ships evacuation.
132. Krasuski, A., & Krenski, K. (2019). A-Evac: the evacuation simulator for a stochastic environment. *Fire technology*, *55*(5), 1707-1732.
133. Kretz, T., Grünebohm, A., & Schreckenberg, M. (2006). Experimental study of pedestrian flow through a bottleneck. *Journal of Statistical Mechanics: Theory and Experiment*, *2006*(10), P10014.Kuligowski, E. D., Peacock, R. D., & Hoskins, B. L. (2005). A review of building evacuation models. Gaithersburg, MD: US Department of Commerce, National Institute of Standards and Technology.
134. Kuligowski, E. (2013). Predicting human behavior during fires. *Fire Technology*, *49*(1), 101-120.
135. Kuligowski, E. D. (2009). *The process of human behavior in fires*. US Department of Commerce, National Institute of Standards and Technology.
136. Kuligowski, E. D., Peacock, R. D., & Hoskins, B. L. (2005). A review of building evacuation models: US Department of Commerce, National Institute of Standards and Technology.
137. Kuligowski, E. (2003). Elevators for occupant evacuation and fire department access. *Cib Report*, 193-200.
138. Lárusdóttir, A. R. (2014). Evacuation of Children: Focusing on daycare centers and elementary schools.
139. Larusdottir, A. R., & Dederichs, A. S. (2012). Evacuation of children: movement on stairs and on horizontal planes. *Fire technology*, *48*(1), 43-53.
140. Law, A. M., Kelton, W. D., & Kelton, W. D. (2000). *Simulation modeling and analysis* (Vol. 3). New York: McGraw-Hill.
141. Layon, A. J., Modell, J. H., Warner, D. S., & Warner, M. A. (2009). Drowning: update 2009. *The Journal of the American Society of Anesthesiologists*, *110*(6), 1390-1401.
142. Law, A. M., & Kelton, W. D. (2000). Simulation modeling and analysis (Vol. 3): McGraw-Hill New York.
143. Zanlungo, F., Ikeda, T., & Kanda, T. (2011). Social force model with explicit collision prediction. *EPL (Europhysics Letters)*, *93*(6), 68005.
144. Lee, D., Kim, H., Park, J. H., & Park, B. J. (2003). The current status and future issues in human evacuation from ships. *Safety Science*, *41*(10), 861-876.

145. Lee, D., Park, J. H., & Kim, H. (2004). A study on experiments of human behavior for evacuation simulation. *Ocean engineering*, *31*(8), 931-941.
146. Leemon, D., & Schimelpfenig, T. (2003). Wilderness injury, illness, and evacuation: National Outdoor Leadership School's incident profiles, 1999–2002. *Wilderness & environmental medicine*, *14*(3), 174-182.
147. Lehnhardt, M., Jafari, H. J., Druecke, D., Steinstraesser, L., Steinau, H. U., Klatte, W., ... & Homann, H. H. (2005). A qualitative and quantitative analysis of protein loss in human burn wounds. *Burns*, *31*(2), 159-167.
148. Lestari, F., Green, A. R., Chattopadhyay, G., & Hayes, A. J. (2006). An alternative method for fire smoke toxicity assessment using human lung cells. *Fire Safety Journal*, *41*(8), 605-615.
149. Li, F., Chen, S., Wang, X., & Feng, F. (2014). Pedestrian evacuation modeling and simulation on metro platforms considering panic impacts. *Procedia-social and behavioral sciences*, *138*, 314-322.
150. Li, D., & Han, B. (2015). Behavioral effect on pedestrian evacuation simulation using cellular automata. *Safety science*, *80*, 41-55.
151. Li, L., Liu, H., & Han, Y. (2019). Arch formation-based congestion alleviation for crowd evacuation. *Transportation research part C: emerging technologies*, *100*, 88-106.
152. Li, X., Geng, Z., Kuang, H., Bai, X., & Fan, Y. (2019). Effect of dangerous source on evacuation dynamics in pedestrian counter flow. *Physica A: Statistical Mechanics and its Applications*, *533*, 122047.
153. Lin, P., Li Gao, D., Wang, G. Y., Wu, F. Y., Ma, J., Si, Y. L., & Ran, T. (2019). The Impact of an Obstacle on Competitive Evacuation Through a Bottleneck. *Fire Technology*, *55*(6), 1967-1981.
154. Lindell, M. K., & Perry, R. W. (2012). The protective action decision model: theoretical modifications and additional evidence. *Risk Analysis: An International Journal*, *32*(4), 616-632.
155. Lindell, M. (2013). The protective action decision model: theoretical, methodological, and practical issues. *Quarantelli Lecture. University of Washington Department of Urban Design and Planning http://visunc. sci. utah. edu/files/Lindell_PADM_QuarantelliLecture. pdf (accessed 27 Feb 2017)*.
156. Lo, S. M., Fang, Z., Lin, P., & Zhi, G. S. (2004). An evacuation model: the SGEM package. *Fire Safety Journal*, *39*(3), 169-190.
157. Lou, B., Qiu, Y., & Long, X. (2017). Maximum smoke temperature in non-smoke model evacuation region for semi-transverse tunnel fire. *Journal of Applied Fluid Mechanics*, *10*(4), 1139-1151.
158. Lovreglio, R., Fonzone, A., Dell'Olio, L., Borri, D., & Ibeas, A. (2014). The Role of Herding Behaviour in Exit Choice During Evacuation. *Procedia-Social and Behavioral Sciences*, *160*, 390-399.
159. Łozowicka, D. (2010). Problems of opposite flow of people during evacuation from passenger ships. *Zeszyty Naukowe/Akademia Morska w Szczecinie*, 82-86.
160. Louka, M. N., & Balducelli, C. (2001). Virtual reality tools for emergency operation support and training. *Proceedings of TIEMS (The International Emergency Management Society), Oslo*.

161. Ma, J., Xu, S. M., Li, T., Mu, H. L., Wen, C., Song, W. G., & Lo, S. M. (2014). Method of bottleneck identification and evaluation during crowd evacuation process. *Procedia engineering*, *71*, 454-461.
162. Manion, P., & Golden, I. J. (2004). Vertical evacuation drill of an intensive care unit: design, implementation, and evaluation. *Disaster Management & Response*, *2*(1), 14-19.
163. Marcus, J. H. (1994). *A review of computer evacuation models and their data needs* (No. DOT/FAA/AM-94/11). Federal Aviation Administration Oklahoma City OK Aeronautical Center.
164. Maria, A. (1997, December). Introduction to modeling and simulation. In *Proceedings of the 29th conference on Winter simulation* (pp. 7-13).
165. MarineSight (January, 2020). Maritime Law, SOLAS. https://www.marineinsight.com/maritime-law/safety-of-life-at-sea-solas-convention-for-prevention-of-marine-pollution-marpol-a-general-overview/
166. Mehran, R., Oyama, A., & Shah, M. (2009, June). Abnormal crowd behavior detection using social force model. In *2009 IEEE Conference on Computer Vision and Pattern Recognition* (pp. 935-942). IEEE.
167. Meng, Q., Zhou, M., Liu, J., & Dong, H. (2019). Pedestrian evacuation with herding behavior in the view-limited condition. *IEEE Transactions on Computational Social Systems*, *6*(3), 567-575.
168. Menin, A., Torchelsen, R., & Nedel, L. (2018). An analysis of VR technology used in immersive simulations with a serious game perspective. *IEEE computer graphics and applications*, *38*(2), 57-73.
169. Mestre, D., Fuchs, P., Berthoz, A., & Vercher, J. L. (2006). Immersion et présence. *Le traité de la réalité virtuelle. Paris: Ecole des Mines de Paris*, 309-38.
170. Miki, K., Mitsuhara, H., Sumikawa, T., Miyashita, J., Iwaka, K., Konishi, M., & Kozuki, Y. (2013). Real world edutainment system and its application to evacuation drills. In *IADIS Int. Conf. e-Soc* (pp. 59-66).
171. Miller, C. (2013). The gamification of education. In *Developments in Business Simulation and Experiential Learning: Proceedings of the Annual ABSEL conference* (Vol. 40).
172. Millington, I. (2007). *Game physics engine development*. CRC Press.
173. Millington, I. (2010). *Game physics engine development: how to build a robust commercial-grade physics engine for your game*. CRC Press.
174. Mitgutsch, K., & Alvarado, N. (2012, May). Purposeful by design? A serious game design assessment framework. In *Proceedings of the International Conference on the foundations of digital games* (pp. 121-128).
175. Mittring, M. (2007). Finding next gen: Cryengine 2. In *ACM SIGGRAPH 2007 courses* (pp. 97-121).
176. Mixamo, (2020). Mixamo, Get Animated. https://www.mixamo.com/#/
177. Miyazaki, K., Katuhara, M., Matsukura, H., & Hirata, K. (2004). Evacuation Simulation for Disabled People in Passenger Ships. *National Maritime Research Institute, Japan*.
178. Mohareb, N. I. (2011). Emergency evacuation model: accessibility as a starting point. *Proceedings of the Institution of Civil Engineers-Urban Design and Planning*, *164*(4), 215-224.
179. Mól, A. C. A., Jorge, C. A. F., & Couto, P. M. (2008). Using a game engine for VR simulations in evacuation planning. *IEEE computer graphics and applications*, *28*(3), 6-12.

180. Molenaar, E. J. (2007). Port state jurisdiction: toward comprehensive, mandatory and global coverage. *Ocean Development & International Law*, *38*(1-2), 225-257.
181. Muda, Z., & Basiron, I. S. (2005, November). Multimedia adventure game as edutainment application. In *International Conference on Computational Intelligence for Modelling, Control and Automation and International Conference on Intelligent Agents, Web Technologies and Internet Commerce (CIMCA-IAWTIC'06)* (Vol. 2, pp. 497-500). IEEE.
182. Muratet, M., Torguet, P., Jessel, J. P., & Viallet, F. (2009). Towards a serious game to help students learn computer programming. *International Journal of Computer Games Technology*, *2009*.
183. P. T. Nastos and A. Matzarakis, "The effect of air temperature and human thermal indices on mortality in Athens, Greece," *Theoretical and Applied Climatology*, vol. 108, no. 3–4, pp. 591–599, 2012.
184. Nevalainen, J., Ahola, M., & Kujala, P. (2015). Modeling passenger ship evacuation from passenger perspective. *Proceedings of Marine Design*.
185. Niininen, O., & Gatsou, M. (2008). Crisis Management— A Case Study from the Greek Passenger Shipping Industry. *Journal of Travel & Tourism Marketing*, *23*(2-4), 191-202.
186. Nilsson, D., & Johansson, A. (2009). Social influence during the initial phase of a fire evacuation—Analysis of evacuation experiments in a cinema theatre. *Fire Safety Journal*, *44*(1), 71-79.
187. Norén, J., Delin, M., & Fridolf, K. (2014). Ascending stair evacuation: what do we know?. *Transportation Research Procedia*, *2*, 774-782.
188. Normoyle, A., Drake, J., & Safonova, A. (2012). Egress online: towards leveraging massively, multiplayer environments for evacuation studies.
189. Nygren, M. (2007). *Simulation of human behaviour in stressful crowd situations*. Numerisk analys och datalogi, Kungliga Tekniska högskolan.
190. (OpenGL Overview, n.d.)OpenGL Setup page, https://learnopengl.com/.
191. Örtqvist, D., & Liljedahl, M. (2010). Immersion and gameplay experience: A contingency framework. *International Journal of Computer Games Technology*, *2010*.
192. Qingge, J., & Can, G. (2007). Simulating crowd evacuation with a leader-follower model. *IJCSES*, *1*(4), 250.
193. Quagliarini, E., Bernardini, G., & Spalazzi, L. (2014). EPES–Earthquake pedestrians′ evacuation simulator: A tool for predicting earthquake pedestrians′ evacuation in urban outdoor scenarios. *International journal of disaster risk reduction*, *10*, 153-177.
194. Quarantelli, E. L. (1975). Panic Behavior: some empirical observations. Retrieved from University of Delaware Library Website.
195. Quarantelli, E. L. (2001). The sociology of panic.
196. Qu, Y., Gao, Z., Xiao, Y., & Li, X. (2014). Modeling the pedestrian's movement and simulating evacuation dynamics on stairs. *Safety science*, *70*, 189-201.
197. Panagiotellis, S. (2017). Evaluation of IOM's second generation intact stability criteria-Investigation for the possible impact on RoRo/RoPax ship design and operation.
198. Papanikolaou, A., Spanos, D., Boulougouris, E., Eliopoulou, E., & Alissafaki, A. (2004). Investigation into the sinking of the ro-ro passenger ferry Express Samina. *International shipbuilding progress*, *51*(2, 3), 95-120.
199. Parisi, D. R., & Dorso, C. O. (2005). Microscopic dynamics of pedestrian evacuation. *Physica A: Statistical Mechanics and its Applications*, *354*, 606-618.

200. Parisi, D. R., & Dorso, C. O. (2006). The role of panic in the room evacuation process. *International Journal of Modern Physics C*, *17*(03), 419-434.
201. Pausch, R., Proffitt, D., & Williams, G. (1997, August). Quantifying immersion in virtual reality. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques* (pp. 13-18).
202. Pelechano, N., & Badler, N. I. (2006). Modeling crowd and trained leader behavior during building evacuation. *IEEE computer graphics and applications*, *26*(6), 80-86.
203. Pelechano, N., O'Brien, K., Silverman, B., & Badler, N. (2005). *Crowd simulation incorporating agent psychological models, roles and communication.*
204. *Ping, P., Wang, K., & Kong, D. (2018). Analysis of emergency evacuation in an offshore platform using evacuation simulation modeling. Physica A: Statistical Mechanics and its Applications, 505, 601-612.*
205. Pirker, J., & Gütl, C. (2015). Educational gamified science simulations. In Gamification in education and business (pp. 253-275). Springer, Cham.
206. Policarpo, F., & Conci, A. (2001, October). Real-time collision detection and response. In *Proceedings XIV Brazilian Symposium on Computer Graphics and Image Processing* (p. 376). IEEE.
207. Proulx, G., & Sime, J. D. (1991). To prevent panic in an underground emergency: why not tell people the truth?. *Fire Safety Science*, *3*, 843-852.
208. Proulx, G. (1993). A stress model for people facing a fire. Journal of Environmental Psychology, 13(2), 137-147.
209. Proulx, G. (2001, May). Occupant behaviour and evacuation. In *Proceedings of the 9th International Fire Protection Symposium* (pp. 219-232).
210. Proulx, G. (2002). *Evacuation planning for occupants with disability*. Ottawa, Canada: Fire Risk Management Program, Institute for Research in Construction, National Research Council Canada.
211. Pu, S., & Zlatanova, S. (2005). Evacuation route calculation of inner buildings. In Geo-information for disaster management (pp. 1143-1161). Springer Berlin Heidelberg.
212. Ramachandran, G. (1990). Human behavior in fires—a review of research in the United Kingdom. *Fire technology*, *26*(2), 149-155.
213. Rapeepisarn, K., Wong, K. W., Fung, C. C., & Depickere, A. (2006). Similarities and differences between" learn through play" and" edutainment".
214. Ren, A., Chen, C., Shi, J., & Zou, L. (2006, June). Application of Virtual Reality Technology to Evacuation Simulation in Fire Disaster. In CGVR (pp. 15-21).
215. Renne, J. (2006). Evacuation and equity. *Planning*, *72*(5).
216. Ribeiro, J., Almeida, J. E., Rossetti, R. J., Coelho, A., & Coelho, A. L. (2013). Towards a serious games evacuation simulator. *arXiv preprint arXiv:1303.3827*.
217. Ripley, B. D. (2009). *Stochastic simulation* (Vol. 316). John Wiley & Sons.
218. Robinette, P., & Howard, A. M. (2011, July). Incorporating a model of human panic behavior for robotic-based emergency evacuation. In *2011 RO-MAN* (pp. 47-52).
219. Roh, M. I., & Ha, S. (2013). Advanced ship evacuation analysis using a cell-based simulation model. *Computers in Industry*, *64*(1), 80-89.
220. Ronchi, E., Fridolf, K., Frantzich, H., Nilsson, D., Walter, A. L., & Modig, H. (2018). A tunnel evacuation experiment on movement speed and exit choice in smoke. *Fire safety journal*, *97*, 126-136.

221. Ronchi, E., Kuligowski, E. D., Reneke, P. A., Peacock, R. D., & Nilsson, D. (2013). *The process of verification and validation of building fire evacuation models*. Gaithersburg: US Department of Commerce, National Institute of Standards and Technology.
222. Ronchi, E. (2021). Developing and validating evacuation models for fire safety engineering. *Fire Safety Journal*, *120*, 103020.
223. Samuelides, M. S., Ventikos, N. P., & Gemelos, I. C. (2009). Survey on grounding incidents: Statistical analysis and risk assessment. *Ships and Offshore Structures*, *4*(1), 55-68.
224. San Chee, Y., & Hooi, C. M. (2002). C-VISions: socialized learning through collaborative, virtual, interactive simulations.
225. Santos, G., & Aguirre, B. E. (2004). A critical review of emergency evacuation simulation models.
226. Schreckenberg, M., Meyer-König, T., & Klüpfel, H. (2001). Simulating mustering and evacuation processes onboard passenger vessels: model and applications. In *International Symposium on Human Factors On Board*.
227. Schröder-Hinrichs, J. U., Hollnagel, E., & Baldauf, M. (2012). From Titanic to Costa Concordia—a century of lessons not learned. *WMU journal of maritime affairs*, *11*(2), 151-167.
228. Seaborn, K., & Fels, D. I. (2015). Gamification in theory and action: A survey. *International Journal of human-computer studies*, *74*, 14-31.
229. Seike, M., Kawabata, N., & Hasegawa, M. (2016). Experiments of evacuation speed in smoke-filled tunnel. *Tunnelling and Underground Space Technology*, *53*, 61-67.
230. SEEN Statistics, https://seen.org.gr/el/m-enimerosi/statistika.
231. Sellers, G., Wright, R,., Haemel, N. (2015). OpenGL Superbible: Comprehensive Tutorial and Reference.
232. Sharma, S., Rajeev, S. P., & Devearux, P. (2015, June). An immersive collaborative virtual environment of a university campus for performing virtual campus evacuation drills and tours for campus safety. In *2015 International Conference on Collaboration Technologies and Systems (CTS)* (pp. 84-89). IEEE.
233. Sharma, S., Amo-Fempong, I., Scribner, D., Grynovicki, J., & Grazaitis, P. (2019). Collaborative virtual reality environment for a real-time emergency evacuation of a nightclub disaster. *Electronic Imaging*, *2019*(2), 181-1.
234. Shiwakoti, N., Sarvi, M., Rose, G., & Burd, M. (2009). Enhancing the safety of pedestrians during emergency egress: can we learn from biological entities? Transportation Research Record, 2137(1), 31-37.
235. Silva, J. F., Almeida, J. E., Rossetti, R. J., & Coelho, A. L. (2013, May). A serious game for EVAcuation training. In *2013 IEEE 2nd International Conference on Serious Games and Applications for Health (SeGAH)* (pp. 1-6). IEEE.
236. Silva, J. F. M., Almeida, J. E., Pereira, A., Rossetti, R. J., & Coelho, A. L. (2013). Preliminary experiments with eva-serious games virtual fire drill simulator. *arXiv preprint arXiv:1304.0726*.
237. Silva, J. F., Almeida, J. E., Rossetti, R. J., & Coelho, A. L. (2013, May). A serious game for EVAcuation training. In *2013 IEEE 2nd International Conference on Serious Games and Applications for Health (SeGAH)* (pp. 1-6). IEEE.
238. Sime, J. D. (1983). Affiliative behaviour during escape to building exits. *Journal of environmental psychology*, *3*(1), 21-41.

239. Sime, J. D. (1985). Movement toward the familiar: Person and place affiliation in a fire entrapment setting. *Environment and Behavior*, *17*(6), 697-724.
240. Sime, J. D. (1995). Crowd psychology and engineering. *Safety science*, *21*(1), 1-14.
241. Simon, R., & Teperman, S. (2001). The World Trade Center attack: lessons for disaster management. *Critical Care*, *5*(6), 1-3.
242. Šmíd, A. (2017). Comparison of unity and unreal engine. *Czech Technical University in Prague*, 41-61.
243. Solomenko, Z., Haroun, Y., Fourati, M., Larachi, F., Boyer, C., & Augier, F. (2015). Liquid spreading in trickle-bed reactors: Experiments and numerical simulations using Eulerian–Eulerian two-fluid approach. *Chemical Engineering Science*, *126*, 698-710.
244. Sorensen, J. H. (1991). When shall we leave? Factors affecting the timing of evacuation departures. *International journal of mass emergencies and disasters*, *9*(2), 153-165.
245. Stefanidis, F., Boulougouris, E., & Vassalos, D. (2019). *Ship evacuation and emergency response trends.* Paper presented at the Design and Operation of Passenger Ships 2019.
246. Tanaka, K., Nagatani, T., & Hanaura, H. (2007). Traffic congestion and dispersion in hurricane evacuation. *Physica A: statistical mechanics and its applications*, *376*, 617-627.
247. Tanimoto, J., Hagishima, A., & Tanaka, Y. (2010). Study of bottleneck effect at an emergency evacuation exit using cellular automata model, mean field approximation analysis, and game theory. *Physica A: statistical mechanics and its applications*, *389*(24), 5611-5618.
248. Terpstra, T., & Lindell, M. K. (2013). Citizens' perceptions of flood hazard adjustments: an application of the protective action decision model. *Environment and Behavior*, *45*(8), 993-1018.
249. Tofilo, P., Cisek, M., & Lacki, K. (2014). The study on the effects of the counter-flow on the evacuation of people from tall buildings. In *Pedestrian and Evacuation Dynamics 2012* (pp. 509-520). Springer, Cham.
250. Unity Game Engine Documentation page, https://docs.unity3d.com/Manual/index.html.
251. Unreal Engine Documentation page, https://docs.unrealengine.com/en-US/index.html.
252. Vairo, T., Quagliati, M., Del Giudice, T., Barbucci, A., & Fabiano, B. (2017). From land-to water-use-planning: A consequence based case-study related to cruise ship risk. *Safety science*, *97*, 120-133.
253. Valanto, P. (2006). Time-dependent survival probability of a damaged passenger ship II—evacuation in seaway and capsizing. *HSVA Report*, (1661).
254. Vairo, T., Quagliati, M., Del Giudice, T., Barbucci, A., & Fabiano, B. (2017). From land-to water-use-planning: A consequence-based case-study related to cruise ship risk. *Safety science*, *97*, 120-133.
255. Vassalos, D., Azzi, C., & Pennycott, A. (2010). Crisis management onboard passenger ships. *Human Performance at Sea, Glasgow*, 1549-1556.
256. Vassalos, D., Guarin, L., Bole, M., Majumder, J., Vassalos, G. C., & Kim, H. S. (2004). Effectiveness of Passenger Evacuation Performance for Design, Operation and Training using First-Principles Simulation Tools, Escape, Evacuation Recovery. *Lloyds Lists Events. London*.
257. Veltman, K. H. (2003). Edutainment, technotainment and culture. *Civita Annual Report*, *2004*, 1.
258. Vøllestad, N. K. (1997). Measurement of human muscle fatigue. *Journal of neuroscience methods*, *74*(2), 219-227.

259. Vorst, H. C. (2010). Evacuation models and disaster psychology. *Procedia engineering, 3*, 15-21.
260. Wainer, Gabriel A., and Norbert Giambiasi. "Application of the Cell-DEVS paradigm for cell spaces modelling and simulation." *Simulation* 76.1 (2001): 22-39.
261. Wang, H., Shi, J., & Mei, J. (2019). Research on the Development of the World's Cruise Industry During 2017–2018: Strong Demands Stimulate the Sustainable High Growth.
262. Wang, J. H., Yan, W. Y., Zhi, Y. R., & Jiang, J. C. (2016). Investigation of the Panic Psychology and Behaviors of Evacuation Crowds in Subway Emergencies. *Procedia Engineering*, *135*, 128-137.
263. Wang, J., Zhang, L., Shi, Q., Yang, P., & Hu, X. (2015). Modeling and simulating for congestion pedestrian evacuation with panic. *Physica A: Statistical Mechanics and its Applications*, *428*, 396-409.
264. Wang, J., Chen, M., Yan, W., Zhi, Y., & Wang, Z. (2017). A utility threshold model of herding–panic behavior in evacuation under emergencies based on complex network theory. *Simulation*, *93*(2), 123-133.
265. Wang, W., Liu, S., Lo, S., & Gao, L. (2014). Passenger ship evacuation simulation and validation by experimental data sets. *Procedia engineering, 71*, 427-432.
266. Wang, Q., Tan, W., & Song, B. (2007, November). Research and design of edutainment. In *2007 First IEEE International Symposium on Information Technologies and Applications in Education* (pp. 502-505). IEEE.
267. Weinberg, S. B. (1978). A premctive model of group panic behavior. *Journal of Applied Communication Research*, *6*(1), 3-9.
268. Wirawan, S., Muhammad, F. F., Saifudin, L. D., Ibrahim, M., & Agushinta, D. (2013). Analysis of child computer interaction in edutainment and simulation games application on android platform in indonesia. *Simulation*, *4*(7).
269. Wong, L. T., & Lo, K. C. (2007). Experimental study on visibility of exit signs in buildings. *Building and environment*, *42*(4), 1836-1842.
270. Xi, M., Smith, S. P., Pisan, N. K., & Blackmore, K. (2015, January). Exploring the reuse of fire evacuation behaviour in virtual environments. In *Proceedings of the 11th Australasian Conference on Interactive Entertainment (IE 2015)* (Vol. 27, p. 30).
271. Yang, L. Z., Zhao, D. L., Li, J., & Fang, T. Y. (2005). Simulation of the kin behavior in building occupant evacuation based on cellular automaton. *Building and Environment*, *40*(3), 411-415.
272. Yi-Fan, L. I., Jun-min, C. H. E. N., Jie, J. I., Ying, Z. H. A. N. G., & Jin-hua, S. U. N. (2011). Analysis of crowded degree of emergency evacuation at "Bottleneck" position in subway stations based on stairway level of service. *Procedia Engineering*, *11*, 242-251.
273. Yoshida, K., Murayama, M., & Itakaki, T. (2001, September). Study on evaluation of escape routes in passenger ships by evacuation simulation and full-scale trials. In *Proc. 9th Interflame Conf*.
274. Yuan, W., & Tan, K. H. (2007). An evacuation model using cellular automata. *Physica A: Statistical Mechanics and its Applications*, *384*(2), 549-566.
275. Zaalberg, R., Midden, C., Meijnders, A., & McCalley, T. (2009). Prevention, adaptation, and threat denial: Flooding experiences in the Netherlands. *Risk Analysis: An International Journal*, *29*(12), 1759-1778.

276. Zafar, M., Zia, K., Saini, D. K., Muhammad, A., & Ferscha, A. (2017). Modeling human factors influencing herding during evacuation. International Journal of Pervasive Computing and Communications.
277. Zhang, G., Jia, H., Yang, L., Li, Y., & Yang, J. (2019). Research on a model of node and path selection for traffic network congestion evacuation based on complex network theory. *IEEE Access*, *8*, 7506-7517.
278. Zhang, Z., Liu, H., Jiao, Z., Zhu, Y., & Zhu, S. C. (2020, May). Congestion-aware evacuation routing using augmented reality devices. In *2020 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 2798-2804). IEEE.
279. Zhao, C. M., Lo, S. M., Zhang, S. P., & Liu, M. (2009). A post-fire survey on the pre-evacuation human behavior. *Fire Technology*, *45*(1), 71-95.
280. Zhen, W., Mao, L., & Yuan, Z. (2008). Analysis of trample disaster and a case study–Mihong bridge fatality in China in 2004. *Safety Science*, *46*(8), 1255-1270.
281. Zheng, X., & Cheng, Y. (2011). Conflict game in evacuation process: A study combining Cellular Automata model. *Physica A: Statistical Mechanics and its Applications*, *390*(6), 1042-1050.
282. Zheng, Y., Jia, B., Li, X. G., & Jiang, R. (2017). Evacuation dynamics considering pedestrians' movement behavior change with fire and smoke spreading. *Safety science*, *92*, 180-189.
283. Zhu, K. J., & Shi, Q. (2016). Experimental Study on Choice Behavior of Pedestrians During Building Evacuation. *Procedia Engineering*, *135*, 206-215.
284. Żydek, K., Król, M., & Król, A. (2021). Evacuation Simulation Focusing on Modeling of Disabled People Movement. *Sustainability*, *13*(4), 2405.

APPENDIX A

Simulator	ACSIT - DPM VR System	VELOS	EVA	Cell_DEVS	EPES
Agent Movement	Conditional	Conditional	N/A	Cellular Automata	Potential (elements of Social Forces)
Agent Behavior	Artificial Intelligence	Artificial Intelligence	Rule-Based	Implicit Behavior	Rule-based
Scalability/No of bots	Not specified	max. 10.000	max. 10.000	At least 1892	N/A
Areas of Application	The area design with Multigen can be very large and the areas can be of any kind. Big cities, farms, vast areas and structures can be designed and represented	Passenger Ships	Multistory Buildings	Multiple areas and disciplines (herein reviewed the human behavior in ship evacuation)	Different areas subject to earthquakes
Users Participation	User controls an agent that performs fire - fighting tasks and participates in the evacuation. The Head-Mounted Display can be mounted to improve immersion.	Yes	Yes	No	No
Perspective	Three-dimensional	Three-dimensional	Three-dimensional	Two-Dimensional	Two-Dimensional

Software	Vega (Virtual environment creation) Multigen Creator (3D building models) Fire Dynamics Simulator (Fire's behavior) Visual C++ 6.0	VRSystem	Unity Game Engine	N/A	• IDE-Eclipse • Alan tool plugin • Java
Development Year	2006	2009	2012	2009	2014
Data Evaluation	• Recording and replaying features. • Calculation and prediction of evacuation routes as a numerical simulation, which consists of the creation of paths in the virtual environment based on the simulation results, the creation a virtual human model with Multigen Creator and the travel of a human model	Three test cases are presented: the first one performs evacuation analysis for a typical scenario in intact condition, using both the simplified and VELOS advanced method; the second one deals with the evacuation analysis in damaged condition using VELOS advanced method, while the third one exploits the simplified	After a short test of the game's control system, real players participated in single game evacuation fire drills. Computer-contr olled bots participated simultaneously. The developers were interested in: The overall evacuation time	To validate this model, the 11 tests noted in the IMO MSC circ.1238 Annex 3 guidance on validation/verification were implemented. The test verified through elementary scenarios that the basic subcomponents work according to the IMO tests.	• This model validates the results of drills conducted by the research team. • Videotapes analyzed for analyzing evacuees behavior. • Analyzing past earthquakes results.

	along the designated path.	method to propose design improvements for the RO - RO (Roll on - Roll off) passenger ship.	(found higher than the real needed time) The behavior and movement of a human during an egress The capabilities of a Game Engine as a developing environment for a Serious Game.		

Table 33. Evacuation Simulators comparison

Game Engine	Portability	GUI	Accepts External Models	Physics Implementation	Controls, Camera, Character	AI tools	Programming Language (s)	Documentation	Complexity	Lightweight	Game Engine
Unreal Engine 4	Yes	Yes	Yes, Easy Process	Yes	Yes	Yes	C++, Block Scripting	Extensive	Low	No	Yes
Unity 5 Game Engine	Yes	Yes	Yes, Easy Process	Yes	Yes	Yes	C#. Boo	Extensive	Low	No	Yes
Cry Engine	Yes	Yes	Yes, Easy Process	Yes	Yes	Yes	LUA	Poor	Medium	No	Yes
OpenGL/ DirectX	Yes	No	Yes, Lengthy Process	No, needs to be coded.	Yes	No, need to be coded.	C++, Java	Extensive	High	Yes	No

Table 34. Game Engines comparison

INDEX B