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CROWDSIM: A FRAMEWORK TO ESTIMATE SAFETY OF EGRESS PERFORMANCE IN REAL LIFE SCENARIOS

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"The mind that opens to new ideas never returns to its original size."
– ALBERT EINSTEIN

"A meeting of individuals is far from being equivalent to the aggregate of their qualities."
– ENRICO FERRI.

"In dreams begins responsibilities."
– DELMORE SCHARTZ.

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CROWDSIM: A TOOL TO ESTIMATE SAFETY OF EGRESS PERFORMANCE IN REAL LIFE SCENARIOS

ABSTRACT

The power of the technology impacts on the modern life in different manners everyday. A variety of scientific models and computational tools have been developed to improve human safety and comfort in built environments. In particular, the comprehension of pedestrian behaviors has higher importance in such context. Moreover, some places are propitious to people agglomeration, i.e. a train station and an airport or even specials events like a sport game. In this thesis we discuss the use of crowd simulation to reproduce and evaluate egress performance in specific scenarios. We present *CrowdSim*: a crowd simulation framework designed to automatically reproduce crowd behaviors during an egress process. A set of software validation tests has been conducted in order to ensure the accuracy of the simulations computed by *CrowdSim*. In addition, *CrowdSim* is able to generate a set of plausible egress plans to be performed in a specific environment and also to rank them. Several case studies were performed in order to evaluate the work. Further, we performed different analyzes, including also the comparison of simulation data against data obtained from real-life experiments.

Keywords: Crowd analyzes, simulation, evacuation plans, egress analyzes.

CROWDSIM: UMA FERRAMENTA PARA ESTIMAR A SEGURANÇA DO PROCESSO DE EVACUAÇÃO EM CENÁRIOS REAIS

RESUMO

O poder da tecnologia impacta constantemente na vida moderna. Diversos modelos científicos, além de ferramentas de computacionais, foram desenvolvidos com o objetivo principal de garantir o conforto e a segurança das pessoas que circulam por um determinado ambiente. Além disso, é possível de fácil observação o fato que muitos ambientes públicos (aeroportos, estações de trem ou rodoviárias além de estádios ou arenas esportivas) são propícios à alta aglomeração de pessoas. Dessa forma, o entendimento do comportamento das pessoas em tais tipos de ambiente torna-se muito importante. A presente tese discute o uso de simulação de multidões como ferramenta para reproduzir e avaliar computacionalmente o processo de evacuação de ambientes aglomerados. A ferramenta *Crowdsim* foi desenvolvida com este fim: reproduzir o comportamento de pessoas durante o processo de abandono de ambientes. Além do desenvolvimento da ferramenta, diversas validações foram realizadas com o objetivo de garantir a qualidade dos resultados produzidos por *CrowdSim*. Além disso, a ferramenta é capaz de gerar automaticamente diversos planos de evacuação possíveis de serem realizados em um mesmo ambiente. Tais planos são avaliados a fim de identificar o melhor plano. Diversos estudos de caso foram realizados com o objetivo de validar esta pesquisa. Diferentes tipos de análises foram aplicados e incluem até mesmo a comparação de dados obtidos com simulação e dados nas mesmas circunstâncias obtidos em um processo de abandono de ambiente realizado na vida real.

Palavras-Chave: Análise de multidões, simulação, planos de evacuação, análise do processo de abandono.

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LIST OF ABBREVIATIONS

ABNT	Brazilian Association of Technical Standards
BAC	Blood Alcohol Concentration
EAP	Emergency Action Plan
EP	Evacuation Plan
FACIN	Faculty of Informatics of PUCRS
FIFA	Fédération Internationale de Football Association
FPS	First Person Shooter
IMO	International Maritime Organization
NFPA	National Fire Protection Association
NPC	Non-Player Characters
RTS	Real-time strategy
SFPE	Society of Fire Protection and Engineering
UEFA	Union of European Football Association
WHO	World Health Organization
XML	eXtensible Markup Language

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1. INTRODUCTION

Enthusiasts from different areas have observed people behavior for many years, decades, or even centuries. Such observation can produce valuable data to be considered as object of study in different fields, from engineering to psychology for example.

In nineteenth century, Le Bon [48] observed that when part of a group, an individual can abandon his/her own mental identity and assumes the identity of the group. Also, the individual can have his/her judgment affected. According to the author, the crowd individuals usually can discard their own values and also their inhibitions which allow them to present behaviors that were not performed when they were alone. Such unusual behavior can develop feelings of different emotions on people. These feelings, i.e anxiety, jitters or panic, make the individual more emotive and sometimes, irrational. Similarly, Sighele [70] highlights situations in which people lost the reason when in crowds and act against different targets, including the own State. Both authors discuss the power of a crowd, which is able to build an uncontrollable and unpredictable force.

Emergent collective behaviors, often unpredictable, can occur when people is part of a crowd, and they can share ideas, feelings and have the same or a similar goal. In addition, recent scientific studies have considered crowds as an entity able to think [50]. In this thesis, we adopted the definition made by Sighele [70], who considers crowd as **a *heterogeneous* and *inorganic* aggregation of people**. He considers as *heterogeneous* because, usually, a crowd is composed by individuals from all ages, gender and different social and cultural realities. In addition, a crowd is considered *inorganic* because its capability to emerge in a sudden way without a formal control and organization.

We know that some places can be propitious to crowd formation. Such places can include, not exclusively, airports and public areas for example. Knowing the existence of places propitious for crowd formation, government, managers, researchers, designers and other professionals are interested in the development of different technologies to improve the evolution of those places, in a smarter and mainly safer way.

Crowd Simulation can be related with entertainment (games and movies) and safety industries. Thinking about entertainment, we can easily apply crowd simulation e.g. in order to populate scenes of a game or movie with bigger, more realistic and dynamic crowds. On the other hand, in the safety engineering, we can observe some open research problems. In this thesis we are going to deal with the problem related to understand the way people leave an environment during an egress process. The possibility of evaluating safety of venues is certainly important in real life crowded environments or events (e.g. Olympic Games at stadiums, train stations, etc.). Such understanding allows engineers to design better places and also to figure out the best way to orient people when choosing a evacuation route.

Different approaches have been proposed in the literature motivating the development of different scientific models along the last decades. Such approaches are concerned with computationally simulate the motion behavior of people, groups of them and even crowds. They were designed based on different goals and were built in different complexity levels. The first known model is a local rules based system [66] able to simulate the behavior of flocks, herds, and schools. Nowadays, complex and different techniques, since navigation fields [57] to different steering algorithms [7, 11], are applied when simulating crowds in order to achieve results coherently with reality.

As observed by Thalmann and Musse [75], aggregated motion is both beautiful and complex to contemplate. Beautiful due to the synchronization, homogeneity and unity described in this type of motion, and complex because there are many parameters to be handled in order to provide these characteristics. There are many characteristics that have been used in scientific literature. According to Fruin [24, 25] crowd behavior is affected by the spatial perception of each individual considering his/her own knowledge and intelligence. When knowing the environment, the individual can make a decision based also on social and cultural patterns. When a specific person decides to move, he or she will also affect how close people can stay of each other and make influence on the personal space of others. According to the American anthropologist Edward Hall, each person has a personal space around the body [30]. Hall denominates this space as *proxemics* and its size can be variable based on the kind of interaction and relationship of the involved people.

In addition to such characteristics, the distance and the kind of relationship among people and crowds can also be affected by the individual characteristics. The individuality can be represented by many factors such as gender, age of each individual and her/his physical state. An important aspect in crowd behaviors is how such factors of heterogeneity can influence the crowd evolution/simulation.

One specific type of crowd literature is interested in crowd evacuation. When simulating crowds, specially during egress, a set of parameters can be considered in order to reproduce coherent behaviors. Such parameters aim to represent:

- *Environment physical structure*: should provide information about building features as dimensions, number of floors, number of rooms, number and localization of exits, stairs location;
- *Environment functionality*: people can act in different ways according to the functionality of the place, such offices, hospital, school, airport, stadiums and arenas;
- *Population data*: number of people in the environment, age, gender, relationship among them, knowledge about the environment; and
- *Environment condition in events*: Many factors can take place in a specific environment affecting its conditions. Such factors can include time of the day (day or night), smoke, fire, heat.

The factors previously presented are just a small set of points that can impact in an evacuation process. The variety of people behaviors based on these and other factors makes complex and challenging the reproduction and virtual simulation of an evacuation process.

Governments Security departments usually specify the need of companies to develop a safety policy in order to deal with emergency situations [76]. Among the requirements, such polices must include emergency escape procedures and route assignments, such as floor plans, workplace maps, and safe or refuge areas. Such requests are because a disorganized evacuation can result in confusion, injury, and property damage. In any emergency scenario, the determination of an optimal or near optimal evacuation plan is currently an open problem. Such issue is related to the identification of the best routes (in different aspects i.e. comfort, time traveled, total time, etc) for a specific population when leaving a building. We believe that the employment of crowd simulation can be considered a powerful tool in order to compute different possible ways to a specific group of people leave an environment. Data from different evacuation plans can provide important information to be analyzed in order to identify the most applicable plan to be performed by a population of a specific building during a possible egress situation.

1.1 Scope of Research

In order to collaborate with the design of safe environments, the research detailed in this thesis is focused on the study of crowd behavior, specially when in egress. When analyzing a specific building, we can note that an egress process can be performed in several different ways. Usually, different evacuations plans can be performed by the same population. Thus, some questions emerge:

1. *Which is the best plan to evacuate a certain building?*
2. *Which factors are important to measure a plan's efficiency?*
3. *Is the total time of evacuation the most important factor when choosing a plan?*
4. *How the many variables existent in a crowd egress impacts the result?*

Aiming to investigate these questions, we developed in this thesis, a study about the use of crowd simulation with the goal to explore evacuation scenarios. Different projects, considering simulation and real exercises, were performed in order to collect evacuation data to support the study. It is important to mention that the base factor of our study focus on the crowd **motion** behavior at a specific environment. External factors as fire, smoke, visibility problems or people health are not part of the scope of this thesis.

1.2 Goals and Methodology

The main goal of this thesis is to present an entire pipeline able to simulate and analyze crowd behaviors when in egress process. In order to accomplish this goal we developed *CrowdSim*, a crowd simulation framework designed to reproduce people's motion behavior paying attention to aspects such human comfort and safety when in large groups.

Since we know that an environment can be covered by different evacuation routes we are interested about investigating possible ways to rank such routes. We believe that simulated data and also information from real life egress exercises can be observed as a powerful source of information in this investigation. By simulating different situations using *CrowdSim*, engineers, designers, and safety managers can study the performance of different evacuation plans and thereby improve such plans as well safety procedures.

The overall pipeline of our research, including work methodology and work contribution, is illustrated in Figure 1.1. The steps of the process are:

1. The environment considered as object of study is totally mapped. The goal is to identify regions where the motion of people is allowed as well as exit routes;
2. Egress data is obtained from simulation and real evacuation exercises;
3. A database of egress data is analyzed in order to identify the best plan to be followed by people when leaving such environment; and
4. The best ranked plan is available to be followed by people when identified an evacuation necessity.

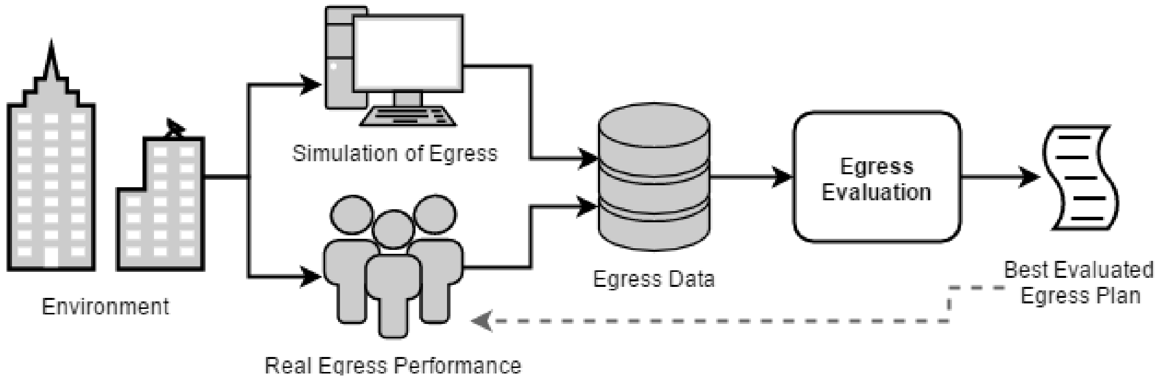

Figure 1.1 – Research overview

In order to reach the main proposed goal, we have specified independent aspects of interest to be achieved during the development of our research. Next section details these aspects.

1.2.1 Specific Goals

The following items summarize the specific goals of this thesis:

- To understand the main aspects related to the behavior of people when part of a crowd, specially during egress situations;
- to investigate the recent scientific work in the field, including commercial production, i.e. existing simulation software;
- to design a software simulation tool able to reproduce crowd motion behavior;
- to guarantee the results computed by the model are accurate with real world situations;

- to investigate ways to generate plausible evacuation plans to be performed in a specific environment;
- to propose a metric to rank the generated plans; and
- to validate our approach:
    a) performing a set of case studies in different scenarios; and
    b) comparing results from the proposed model against real data egress exercises.

1.3 Organization of the Thesis

For the best organization of the text, this thesis is divided in 7 chapters, including the current Introduction chapter.

Next chapter (Chapter 2) details some important theoretical background which aims to facilitate the understanding of the thesis. We explore concepts related to crowd dynamics in different areas, such as psychology and safety. Such concepts are important because they provide insights to ease the research development. Also, safety requirements, from different government guidelines are verified.

Chapter 3 presents the related work identified with main goal to support our research. We focus on computationally simulated crowds in order to observe egress behavior. In addition we try to identify commercial softwares that nowadays look for the same goal.

In Chapter 4 we present an overview of *CrowdSim*, detailing the two main models that compose it: *Configuration* and *Simulation*. In addition, we explain how we work with heterogeneous crowds and we also detail the module able to generate and evaluate evacuation plans. Such module was developed in order to identify the best plan to be performed by a population in a specific environment.

Software validation is explained in Chapter 5. Firstly, we discuss the importance of such type of approach in simulation software. Secondly, in order to verify the accuracy of simulations computed by *Crowdsim*, we performed a set of test cases, in different categories, aiming to check the software performance. International guidelines [41] were considered as basis of the tests.

Experimental results are presented and detailed in Chapter 6. Several projects were detailed where we applied *CrowdSim* to reproduce and also analyze evacuation process. These projects contemplate different environments, such as a sport stadium, a night club, a college building among others.

Finally, considerations about the work developed are made in Chapter 7. The chapter summarizes the contributions of the research and presents a set of plausible future work.

2. BACKGROUND

This Chapter presents the main concepts related to our research. Once we work with different knowledge areas, it is interesting to firstly discuss them. We observe points related with crowd dynamics, in normal as well as egress situation, in order to find insights that could cooperate with the research development.

First of all it is interesting to define some aspects related to crowds. We know, as previously defined, that crowd represents a large group of individuals in the same environment. Despite that, its formation can occurs in a voluntary or non-voluntary way, in every day situations as well as in specific cases (i.e. panic or emergency). This is a simple, but very important, concept that we illustrate in Figure 2.1: people voluntary accept to be part of a crowd formed by the audience of a music festival (a). On the other hand, a crowd involuntarily have emerged during the evacuation process which was performed during 9/11 events (b).


(a) (b)

Figure 2.1 – Two different examples of crowds which have emerged in two very different circumstances: happiness during a music festival (a) and panic during the event of 9/11 (b).

In order to identify a large group of people as a crowd, some criteria are interesting to be observed. Challenger [17] highlights some of them:

- *Size*: there should be a measurable gathering of people.
- *Density*: crowd members should be co-located in a particular area, with a sufficient density distribution.
- *Time*: Individuals should typically come together in a specific location for a specific purpose over a measurable amount of time.
- *Collectivity*: crowd members should share a social identity, common goals and interests, and act in a coherent manner.
- *Novelty*: individuals should be able to act in a socially coherent manner, despite coming together in an ambiguous or unfamiliar situation.

As different events and circumstances can be the stage for crowd formation, some researchers have worked in order to categorize the different kinds of crowds. There is no one typical crowd, but a range of crowd types, each with their own characteristics and typical behaviors. As far as we know, there is no much research in order to sort crowd types. Berlonghi [6], in 1995, have identified five different types of crowds. In order to illustrate such types, we searched on internet some images that are illustrated in Figure 2.2[1] and follow described:

- *Spectator*: A crowd watching an event that they have come to the location to see, or that they happen to discover once there (Fig:2.2(a)).
- *Demonstrator*: A crowd, often with a recognized leader, organized for a specific reason or event, to picket, demonstrate, march, or chant (Fig:2.2(b)).
- *Dense or Suffocating*: A crowd in which the movement of people decreases faster and sometimes can stop. Due to high crowd density, with people being swept along and compressed, resulting in serious injuries and fatalities from suffocation (Fig:2.2(c)).
- *Violent*: A crowd attacking, terrorizing, or rioting with no consideration for the law or the rights of other people (Fig:2.2(d)).
- *Escaping*: A crowd attempting to escape from real or perceived danger or life-threatening situations, including people involved in organized evacuations, or chaotic pushing and shoving by a panicking mob (Fig:2.2(e)).

Since we know the attributes that can be observed to characterize and also to understand different types of crowds, next section details aspects regarding to crowd dynamics. Our goal is to study crowds concepts in order to mainly understand how they are likely to move and behave.

2.1 Crowd Dynamics

The observation of crowd evolution into a specific place allow us to observe different aspects. Among them, it is interesting to highlight the fact that a crowd is composed by independent individuals and each one has his/her own needs and desires, but all of them share the same goal. Such feeling is highlighted by Osorio [56], a psychologist who defines a group of people as a human system composed by the set of people able to know each other on they own singularity. In addition these people are sharing goals and performing a collective action.

The understanding of people behavior is a huge research field in psychology area since centuries ago. On the beginning of 20th century, Freud already have developed studies involving the observation of people behavior for decades [23]. Supported by studies from LeBon [48] e Mc Dougall [49], Freud discuses about the behavior of human beings when part of a group and define crowd as a temporary entity, consisting of heterogeneous elements that have joined together for a moment.

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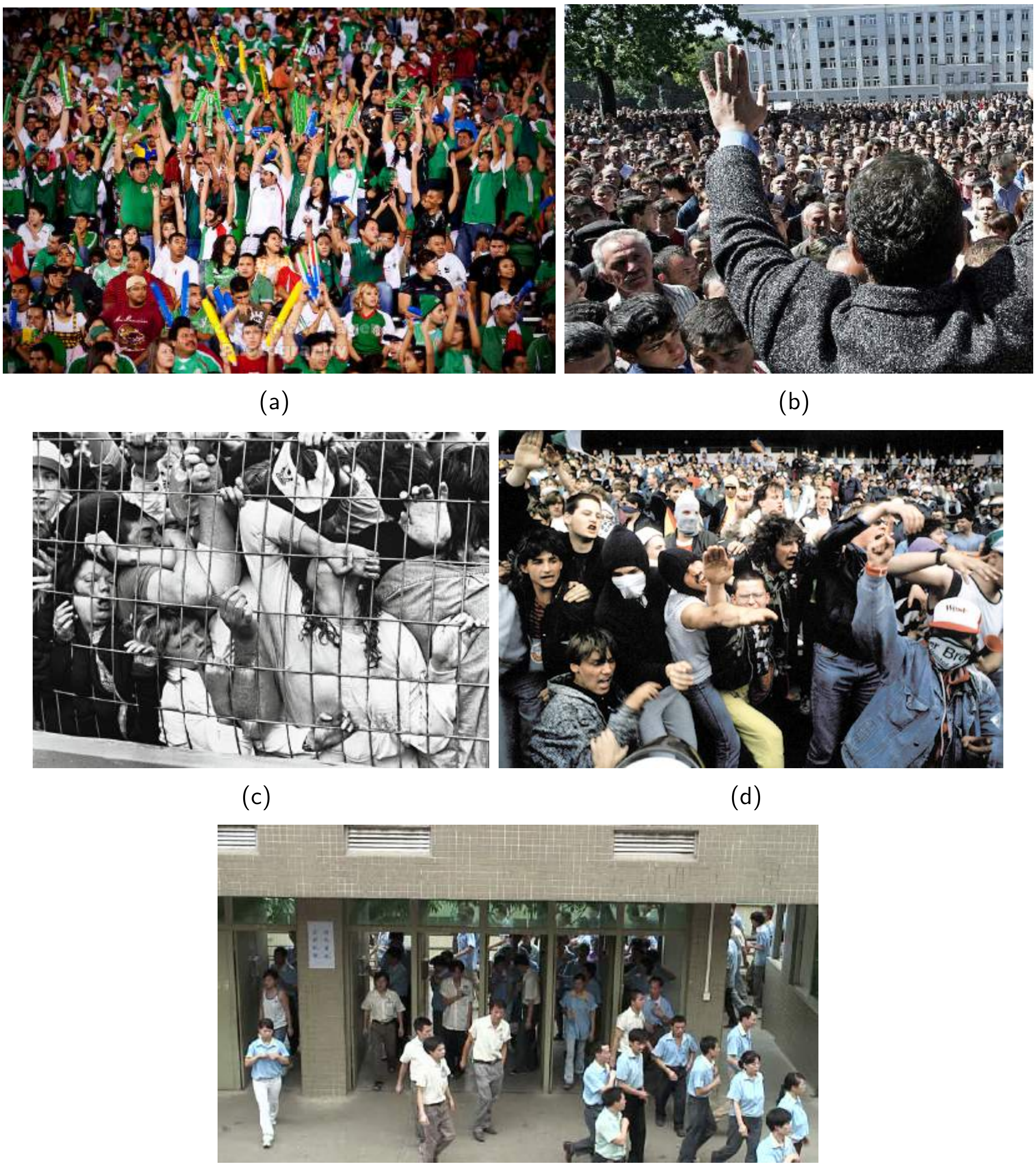
[1] Images from the Internet



(a) (b) (c) (d) (e)

Figure 2.2 – The five types of Crowds according to citeBerlonghi:1995: spectator (a), demonstrator(b) dense or suffocating (c), violent (d) and escaping (e).

Many other aspects were observed in the same field in past centuries. One of them it is very important to mention and was firstly observed by LeBon [48] who says that when part of a crowd, the individuals can perform unusual behaviors; behaviors which he or she is not able to perform alone. In this kind of situation the individuals can act in a collective way and a crowd thinking emerges as a new entity. This new entity can make people feel, think and act in different ways, also being able to perform dangerous behaviors which can also be responsible by fatality moments.

We know that a crowd is a congregation of people in the same environment, despite that it is important to take in mind that every individual member of a crowd is owner of his or her own personal space in the environment. The American anthropologist Edward Hall, based on the personal space idea, have presented in 1966 the concept of *proxemics* [30] in order to represent the personal space of each person. The author also explain that the distance between people, when interacting with each other, varies according to their levels of intimacy. These levels are divided in four possible ranges (see Fig. 2.3): *intimate* $[0.00, 0.45]m$, *personal* $(0.45, 1.20]m$, *social* $(1.20, 3.60]m$ and *public* $(3.60, 7.60]m$.

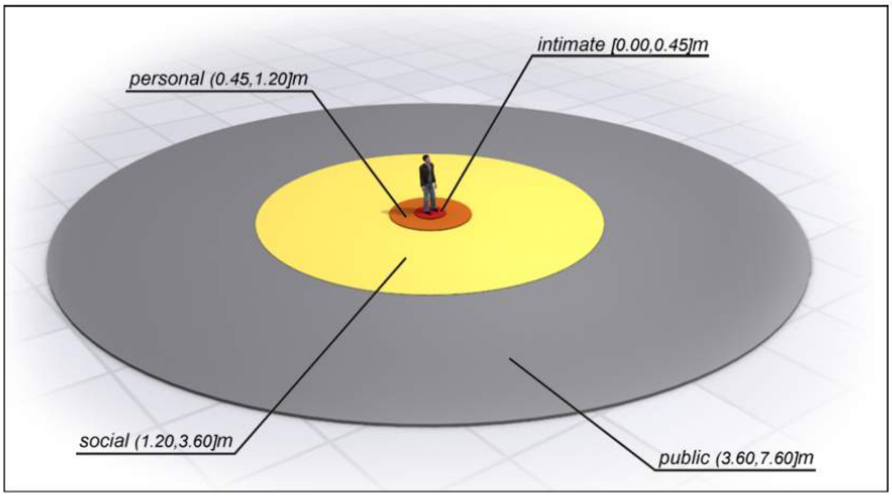


Figure 2.3 – Illustration of a person proxemics based on Hall's definitions of distances: intimate, personal, social and public.

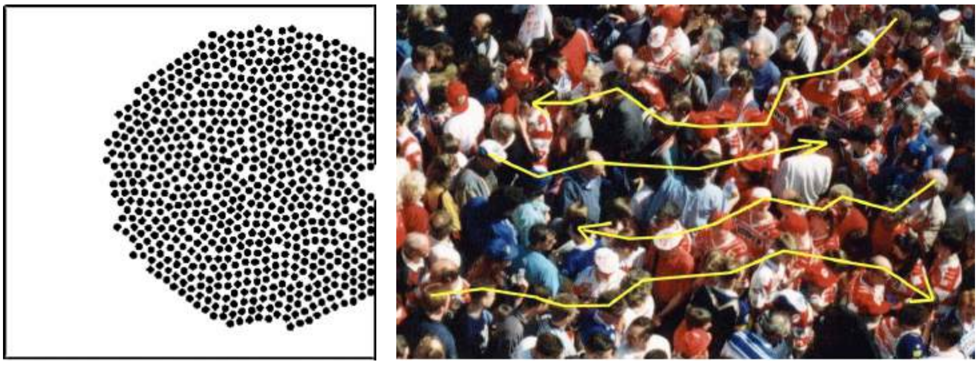
It is important to mention that the concept of *proxemics* applied to individuals, can also be observed and applied for groups of them. Such aspect is considered because groups of people can perform different behaviors based on its size, place or even the relationship among the group members. In this way, when knowing the social space of a group it is possible identify its relationship with the environment, i.e the destiny or direction of a group of people walking together [21].

Still [73] have studied people behavior along last decades. During his Ph.D., he developed a set of computer programs in order to study, and also reproduce, the behavior of a crowd. His framework, called *Legion* was developed based on four rules to determine the functions for the flow of human traffic. These rules interact as characters come into proximity with each others space associated with the static and dynamic objects in the environment. The result exhibits emergent behavior, specifically, the entities are programmed with one kind of behavior but the group of entities exhibits another one. Where the group behavior cannot be reduced to the individuals' behavior, a system is defined as emergent.

Despite the simulation results, Still's research also have pointed important behaviors that can emerge from real crowds and were also observed by other authors as well [35] and recognized by international institutions [17]. Follow we summarize some of these behaviors, which are interesting to be reproduced when working with crowd simulation:

- *Arch Formation*: It happens when a large, dense crowds push forward towards a narrow exit. In situations like this, clogging and arching are observed; *i.e.* the exit becomes clogged and the crowd forms an arch-shape in front of the exit.

- *Lanes Formation*: When people move in the same or opposing directions, they can self-organize to create distinct lanes: one for each direction of movement or taking into account the different velocities. This self-organization phenomena helps to reduce collisions and increase the motion speed. However, in high density or nervous crowds, any lanes formed may break down due to continuous overtaking maneuvers.
- *Corner Effect*: As crowd members turn corners, they tend to slow down and move further into them, becoming more densely packed and appearing to *hug* the corner.
- *Ring Effect*: This phenomena emerges when a crowd is observing a particular event or gathers around a particular point of interest, such as a street artist. In cases like this, a ring structure emerges, radiating outwards from the point of interest.
- *Speed reduction effect*: this effect arises when many people are populating a specific environment, and more arrives. In this case, the velocity can be decreased.
- *Principle of Least Effort*: When possible, crowd members will typically take the fastest route. They aim to minimize time and costs, avoid congestion and maximize their speed.



(a) Arch Formation [82]　　(b) Lane Formation [73]

(c) Corner Effect　　(d) Ring Effect

Figure 2.4 – Crowd organization examples (Non-referenced figures are available on the Internet).

As we detailed some important aspects related to crowds in a general way, next section specifies some aspects observed in crowds evolution during an egress process.

2.2 Crowd Evolution in Egress Situations

As very well observed by Lebon [48], when in crowds, people can perform unusual behavior which can be responsible to irrational actions. Indeed, we can say that such actions can even be increased under panic egress cases. It is very easy to look back in history in order to point out some important facts which requested from crowds, an involuntary evacuation. In this way we highlight:

1. Atomic bombing of Japan during World War II;
2. Terrorists reach New York in 2001;
3. Hurricane Katrina in 2005.

These are just three examples which requested evacuation and were occasioned by different events. In such evacuations people probably were drove by their simple emotions and answered the situation performing irrational behavior.

The success of an evacuation event can be related with the well understanding of the process. In order to reach the success we can point three important factors: interpretation, preparation and action [52]. We can understand *interpretation* as the moment when people observe the real need of an evacuation; *preparation* is regarding to plan the best route to follow while action means the motion through the chosen route in order to reach a safe area. In addition, the understanding of other specific aspects is widely necessary. Such points are regarding to:

- Building type: office, airport, train station;
- The understanding of occupants' behavior under panic situation;
- Occupants distribution (includes age, gender and disability); and
- Location of dangerous areas as well as safe places and emergency exits.

The knowledge about previous aspects facilitates the execution of a safe egress process. Nowadays, the evolution of a crowd during an evacuation process usually shows behaviors that can evidence the well organization and structure of the group. This is due to cooperation and coordination performed by the people [19].

Usually, the group has the power of influence the members motion. In other words, the choice of escape route, *made individually*, usually is also influenced by the actions of the other members of the crowd. This aspect can justify the fact of when in egress, people typically move in the same direction as others. In this way, for Cocking & Drury [19], when united by an emergency situation, a physical crowd (a group of individuals in the same location, each with his or her own personal identity) may be transformed into a psychological crowd (i.e., a group of people united by a common social identity as members of a particular category). Additionally a set of extra factors (mapped by [17]) may to influence an evacuation process:

- *Mobility*: an individual who is less mobile is likely to need longer to evacuate in an emergency.
- *Physical Position*: an individual lying down is likely to have a slower rate of reaction and movement than an individual standing up.
- *Density*: crowd movement will be slower in a more densely packed environment.
- *Alertness*: an individual who is less alert, for instance as a result of tiredness or intoxication, is likely to react more slowly in the event of an emergency.
- *Visibility*: the more visible the signage and emergency exit routes, the more attractive they are likely to be to crowd members and the more likely (and at higher speed) crowd members are to follow those routes.
- *Complexity of the environment*: the more complex the environment, the more indecisive individuals are likely to be and the longer it is likely to take to evacuate.

These points are important and usually can be considered in order to regulate egress process. Government groups and different organizations have been worked in regulate egress process. Next section presents and details some of such regulations.

2.3 Regulations for Evacuation Process

Nowadays, governments and professionals from different fields work in order to specifies effective measures with goal to define optimal evacuation plans. The accurate definition of an evacuation plan is aimed in order to guarantee people safety when leaving a building, specially when a panic or an attention situation occurs. The evaluation of egress details is already requested by international organizations as UEFA (Union of European Football Association) or FIFA (Fédération Internationale de Football Association) in specific sites as sport places, stadiums and arenas, beyond specific regional regulations.

UEFA express some concerns related to egress processing which must be observed since the design of a new stadium starts [22]. The safe capacity is a mandatory requirement which focuses, as the name suggests, on ensuring maximum safety for spectators. It is widely accepted that all spectators should be able to exit the stadium bowl to a point of safety within a maximum of eight minutes. This value based on a maximum flow rate through the stadiums exits of 660 people an hour. However, there may be some scope for specifics variations based on the size and design of the venue.

According to FIFA, the emergency evacuation time is in part based on the level of risk and the available emergency evacuation routes to places of safety and/or places of reasonable safety. The organization have published a guideline[2] where they define a set of Stadium Safety and Security Regulations. According to such guide, factors like the type of construction and materials used in the

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[2] `fifa.com/mm/document/tournament/competition/51/53/98/safetyregulations_e.pdf`

stadium will have an impact on the calculation of the suggested time for evacuation. In addition, fire is one of the major risks to be considered when calculating the acceptable egress time. For example, if the risk of fire is high due to the construction of the stadium, the expected evacuation time must be reduced.

The emergency evacuation time is not a fixed value. It is a calculation which, together with the appropriate rate of passage, is used to determine the capacity of the emergency exit system from the viewing accommodation to a place of safety or reasonable safety, during an emergency.

The United States of America considers the *Life Safety Code* [1], a guideline developed by the National Fire Protection Association (NFPA) which provides details to be followed during a possible building evacuation process. Together with the *Design Handbook* provided by the Society of Fire Protection and Engineering (SFPE) [39], building designers can observe, during the project phase of a building, egress aspects regarding to features as sprinklers, exit lights and alarms.

According to the *International Building Code* [40], every building or structure, new or old, designed for human occupancy shall be provided with exits sufficient to permit the prompt escape of occupants in case of fire or other emergency. According to the guideline, all exits should discharge directly to the street or other open space that gives safe access to a public way. The streets to which the exits discharge shall be of width adequate to accommodate all persons leaving the building. An *emergency action plan* - EAP, according to the guideline, should cover those designated actions that ensure employee safety from fire and other emergencies:

- Emergency escape procedures and emergency escape route assignments;
- Procedures to account for all individuals after emergency evacuation has been completed;
- The preferred means of reporting fires and other emergencies; and
- Names or regular job titles of persons or departments who can be contacted for further information or explanation of duties under the plan.

Independently of the guideline, it is important to mention that the personal behavior of the people can contribute to the emergency of congestion that are not predicted during an egress plan development.

The legislation about crowd management in Brazil is under development. The attention in the area have increased along the last years. Such growing is explained due to the some specific events. Firstly, a sad disaster that occurs in a night club: Kiss Night Club [3]. In addition, big sportive events that take place in the country (World Cup and Olympics) are helping to determine the new legislation.

The Brazilian Association of Technical Standards (ABNT) has defined, in 2001, the guideline NBR 9077:2001 aiming to specify regulation concerned about emergent exits. According to the guideline, the concentration of people when using and emergency exit should be until $2 people/m^2$.

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[3] `edition.cnn.com/2013/01/28/world/americas/brazil-nightclub-fire.`

The Technical Guideline from the government of São Paulo - Brazil [64], defines specific points regarding to people safety when in egress. We summarize some of the most important:

- The individuals should achieve a safe point without walking no more than 20 meters in outdoor areas and 10 meters on indoor areas. Emergency exits can be considered as the safe point.
- The time to a group of people leave a public indoor area, such as a theater, should no exceed 6 minutes.
- The concentration of people in stand up areas should not be greater than 4 people/m2.

We opted to present data From São Paulo due the fact the city is considered the most important city of Brazil. It is important to mention that each state or city can provide their own building regulation, if there are not federal regulations.

3. RELATED WORK

Crowd simulation have been studied over recent decades [75]. Nowadays we can observe a huge number of researchers working in order to provide coherent and realistic simulations applied in areas such as engineering, safety systems and digital animation. In order to predict people behavior, computational models are requested to produce results in a realistic way when compared with people behavior in real world.

The works mentioned in this section aim to give an overview of recent methods focused on crowd and egress simulation, evacuation plans and the possibility of dealing with heterogeneous agents. Despite the goal, crowd simulation models can be classified as *macroscopics* and *microscopic* approaches. Hamacher & Stevanus [31] produced a survey classifying different evacuation models and also define such categories:

- *Macroscopic models* are mainly used to produce good lower bounds for the evacuation time and do not consider any individual behavior during the emergency situation. The simulation results can be used to analyze existing buildings or help in the design phase of planning a building. A special feature of the presented approach is the fact, that travel times of evacuees are not restricted to be constant, but may be density dependent. Using multicriteria optimization priority regions and blockage due to fire or smoke may be considered.

- *Microscopic models* are able to model the individual evacuee's characteristics and the interaction among evacuees which influence their movement. Some probabilistic laws for individual evacuee's movement are sometimes employed in these set of models.

Challenger *et al.* [17], based on the concepts of Macroscopic and Microscopic models, have organized important simulation models into different sub-categories that we sort in Table 3.1.

We know that crowd simulation is a huge research field and have motivated the development of several other approaches. Diverse macroscopic and microscopic approaches have been proposed in order to reach the point of well accurate reproduction of people behavior. Moreover, we can also observe some approaches that combine the efficiency of Macro Modeling (equation-based modeling) and the advantages of Micro Modeling (agent based modeling) [4].

Along last decades, different techniques were developed in order to provide simulation with a great level of coherency with real world. Nowadays, simulation can be developed in order to consider a single building, as well as an entire community populated by large crowds [79, 84]. Applications of crowds methods are not necessarily concerned with evacuation behaviors; they can be object of study in different areas, since to entertainment until safety engineering. Robust algorithms can be applied to animate, control, and author human-like agents having their own set of unique capabilities, personalities, and desires [44].

Macroscopic Models	Pregression Models	pedestrian flow under specific circumstances, dependent on the infrastructure (e.g., stairs, corridors), from statistically established relations between flow variables [51]
	Route Choice Models	pedestrian way-finding, based on the premise thatpedestrians chose their route in order to maximize utility, in terms of travel time, effort, comfort, etc [37]
	Fluid Dynamics or Gas Kinetics Models	These describe the movement of individuals within a crowd as being continuous and fluid-like with changes in density and velocity over time [36]
Microscopic Models	Rule-Based Models	For example, Reynolds' (1987, 1999) *boids* model [66]
	Social Forces Models	Each individual is represented by a self-driven particle subject to social and physical forces [34, 35]
	Cellular Automata Models	These models divide the environment into a uniform grid of discrete cells, with agents able to move between unoccupied neighboring cells [10]
	Agent-Based Models	These are the most complex and realistic of the simulation models. They are modeled as a collection of intelligent,autonomous, decision-making entities known as agents [20]

Table 3.1 – Macroscopic and Microscopic approaches to crowd simulation organized into subcategories [17].

Follow we describe the main approaches related to our work. We opted to focus in two ways. First we detail scientific approaches in order to map the state-of-the art regarding to crowd evacuation. Next we present a set of commercial simulation available nowadays in the market.

3.1 State-of-the-art

An important work regarding to reproduce crowd behavior when in egress was proposed by Braun *et al.* [12]. The authors explore the agents personal characteristics in order to simulate different reactions and behaviors during an evacuation process. Inspired on a physically based approach [34] the authors aggregate a set of features to simulate agents and also groups in order to reproduce a heterogeneous crowd. Such features include, among others, aspects as families representation, dependency level from others, level of agents altruism and also desired velocity. The authors keep groups together considering a force composed from the altruism level from agents of the same family. In addition, based on the altruism level, an agent can ungroup from his or her family in order to help other agents in the process.

The work from Zhu *et al.* [83] was developed observing 2008 Olympic games, in China. At that time, the authors developed an approach able to reproduce pedestrian traffic created from delegations of athletes from different countries and also, the audience. A case study was performed considering the *National Stadium* and taken into account aspects as the number of pedestrians and its distribution into specific situations (such the final moments of a game).

Simulate the usual process of evacuation was the simple and punctual goal envisaged by *Fu et al.* [26]. The motivation for the authors was to reproduce the pedestrian behavior in order to represent exit selection taking into account a least effort cellular automaton algorithm. It is represented by a set of 2D cells where we can find pedestrians or obstacles. The motions and goals used to guide the movements are defined considering a probabilistic approach. The use of automaton cellular algorithms are also present in the work of Ji *et al.* [42] in order to simulate pedestrian dynamics as well as by Aik and Choon [3] with main goal to reproduce a simple evacuation process. Chu *et al.* [18] developed the platform SAFEgress (Social Agent For Egress), in which building occupants are modeled as agents able to make their actions according to their knowledge of the environment and their interactions with the social groups and the neighboring crowd. According to the authors, results show that both agents familiarity with the building and social influence can significantly impact evacuation performance.

Pelechano and collaborators [58] have explored different aspects regarding to virtual crowds behaviors. One aspect studied by the authors is concerned to improve a crowd simulation systems by the addition of a psychological model [61]. In this way, the authors, presented a framework that combines the *PMFserv* framework [71] (mature models for physiology, stress, perception and emotion) with their Multi-Agent Communication for Evacuation Simulation (MACES) system [59]. The integration allowed th crowd simulation model to provide events that an agent can perceive, resulting in responsive, reactive, and situated behaviors.

A review of crowd simulation models and selected commercial software tools for high rise building evacuation was developed Pelechano & Malkawi [60]. The goal of the work was to study the importance of incorporating human psychological and physiological factors into the crowd simulation models. The authors presented an overview of fundamentals that should be applied to simulate human movement closer to real movements of people, where interaction between bodies emerges and flow rates, densities, and speeds become the result of those interactions instead of some predefined value.

It is important to mention that besides agents and environment, some externals factors can make influence on the results of a simulation. Such external factors can include, not exclusively, aspects of fire and smoke propagation. This aspect was object of study of Huang *et al.* [38]. The authors have focused the work in crowd simulation, but considering some distinct aspects such as smoke into the simulation. The authors developed MIMOSA: Mine Interior Model Of Smoke and Action, which integrates an underground coal mine virtual environment, a fire and smoke propagation model, and a human physiology and behavior model. Each individual agent has a set of physiological parameters as variables of time and environment, simulating a miner's physiological condition during normal operations as well as during emergencies due to fire and smoke.

Xi and Smith [81] developed a Virtual fire evacuation training systems. The idea was focused on extend a virtual environment development pipeline for building virtual fire evacuation training systems. The authors investigates the best way to integrate 3D building models and fire egress behavior from fire evacuation simulations into an example game engine. The aim is to ensure that the behavior of autonomous agents, representing human evacuees extracted from the fire simulator, is faithfully represented in the target virtual environment. A pipeline is presented as example in order to show the integration of google sketch up[1], FDS+Evac [45] and Unity 3D[2].

Beyond the analyzes of agents' behaviors when simulating crowds it is very important to consider the way in the environment can contribute with a possible egress process. This is one of the goals considered on the research developed by Berseth *et al* [9] who observe that the layout of a building, affects the flow patterns of its intended users. The authors propose a computational framework for studying the configuration of architectural building elements. Such elements can represent pillars or doors and are studied in order to optimize dense pedestrian flow during building evacuations. One of aspects considered by the authors was the effect of local collision avoidance strategies used in crowd flow patterns on representative evacuation benchmarks. The benchmarks include variations on the number and placement of pillars, exit door sizes, as well as corridor and crowd flow configurations. Three different steering algorithms (ORCA [77], PPR [72], SF [34]) was applied in order to observe the optimizations identified by the proposed suite. According to the authors, when the main goal is to study real buildings, it should be important to provide approaches developed and validated by the community. In addition, they conclude that, door widths are an important aspect observed in the work. Such element had a significant impact on crowd flow patterns, especially for bi-directional traffic, which highlights the importance of selecting the right door width based on the expected crowd interactions.

In the same way, thinking about the environment structure, the work presented by Jiang *et al*. aims to increase the environment safety by analyzing the better placement of the obstacles [43]. In order to attend the goal, the authors developed genetic algorithm based on social-forces. According to them, simulation results indicate that appropriately placing two pillars on both sides but not in front of the door can maximize the escape efficiency. In order to validate results, was performed a Human experiments using 80 participants. Results indicated that people correspond well with the simulations.

The information about motion is considered by Rodriguez *et al* [67], who investigate the use of tools in robotics and control to improve the design of buildings. The authors apply methods of optimization and roadmap-based motion planning to determine how placement of agents and common design features, such as pillars and doors, can affect the flow of human traffic through a building . Some points that were object of experiments have explored such aspects: pedestrian flow Rate optimization via pillar placement; evacuation time Via door placement and the optimization of agent encounter.

After have defined an ideal environment, it is also interesting to define the ideal parameters to possible steering algorithms. This aspect is also aimed by Berseth and collaborators [8]. The authors present a methodology for automatically fitting the parameters of a steering algorithm. The goal is to minimize any combination of performance metrics, across any set of environment benchmarks in a general, model-independent fashion. Called *SteerFit*, the framework can optimize steering algorithms according to different criteria: distance, time, or energy consumption of an agent, its

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[1] `sketchup.com`

[2] `unity3d.com`

computational performance, similarity to ground truth, user-defined custom metrics, or a weighted combination of any of them. The framework was applied in order to fit parameters for three steering algorithms: ORCA [77], PPR [72], SF [34]. According to the authors, the parameter fitting can be used to improve the performance of an specific algorithm. The optimization also can be considered as an analysis tool able to produce a detailed view of an algorithm's behavior relative to its internal parameters.

Beyond the simulation of one way of egress, it is interesting to observe different ways to people leave an environment. One alternative for egress plan generation is the use of matheuristic. The work of Pillac *et al.* [62] presents an evacuation algorithm that follows recommended evacuation methodologies, which divide the evacuated area in evacuation zones, each being instructed to leave at a specific time and following a pre-defined route. According to the authors, the *Conflict-Based Path-Generation Heuristic* specifies evacuation routes for each evacuation zone and uses a lexicographic objective function that first maximizes the number of evacuees reaching safety and then minimizes the total evacuation time. The algorithm was evaluated taken into account real-scale, massive flood scenarios in the Hawkesbury-Nepean river, Australia. The simulation considered 70,000 agents which require evacuating the area.

One of the main points considered when simulating crowds is concerned with results validation. The proper way should be to compare data from simulation with real-life experience. Current studies indicate this as a challenging point. Nowadays, there is just a few data driven models developed in order to validate information from simulation and real life. As part of this small set of studies, we can describe the work presented by Murphy *et al.* [53]. In such work the authors present EvacSim, a multi-agent building evacuation simulation. In this work, the authors detail a pedestrian model elements that govern microscopic agent movement such as personal space preservation, obstacle avoidance and moving together as a crowd. In order to validate the EvacSim pedestrian model against real-world pedestrian data, the authors made a comparison of flow rates, density and velocity for corridor entry and for merging groups, considering data from simulation and real world in a controlled environment.

The work of Guy *et al.* [28] developed a statistical similarity measure for aggregate crowd dynamics. The method aims to measure the similarity between a given set of observed, real-world data and visual simulation technique for aggregate crowd motions of a complex system consisting of many individual agents. This metric uses a two-step process to quantify a simulator's ability to reproduce the collective behaviors of the whole system, as observed in the recorded real-world data.

Wang *et al.* [78] propose a new approach based on finding latent Path Patterns in both real and simulated data in order to analyze and compare them. Unsupervised clustering by non-parametric Bayesian inference is used to learn the patterns, which themselves provide a rich visualization of the crowd's behaviour. To this end, we present a new Stochastic Variational Dual Hierarchical Dirichlet Process (SV-DHDP) model. The fidelity of the patterns is then computed with respect to a reference, thus allowing the outputs of different algorithms to be compared with each other and/or with real data accordingly.

3.2 Commercial Simulators

Crowd management is widely applied with goal to provide important information regarding to people behavior. One of the major strategies to ensure audience safety is by practicing effective crowd management strategies.

The police of United States observes that one of the most important challenges facing police executives is the need to prepare their departments for major events control. The institution have published a report which aims to explore some of the key issues that have proved important or difficult in the real world of major events management [63]. This kind of management help event's organizers to identify agglomeration areas, bottlenecks regions as well as attention points and other situations. Nowadays, important events are supported by crowd management teams.

More specifically, one part of crowd management is related with egress situation. Egress problems can be observed in different types of systems, such as buildings, cities or transportation. The use of a simulation software allow safety engineers to validate, explore and also predict the crowd behavior in a specific building or outside environment without the need to involve real people. In addition, such possibility is even more important when simulating a building during its design phase identifying improvement and attention points in able time to be fixed. It is possible to identify diverse positive points about the use of a commercial software to produce crowd simulations. Among such aspects, we can highlight:

- Reproduce the exact desired scenario, including situations of panic which are difficult to be performed by humans when in training. In addition, visualize any possible crowd related incident and improve preparedness;
- Avoid the high training costs of practical training;
- Learn the necessary skills in a safe and realistic environments.

In order to produce realistic results and also, to predict crowd behaviors aiming to alert events managers, some commercial software are currently used by crowd management teams in different countries. Next sections describe important commercial crowd simulators available in the market. Each of them is detailed and explored in order to evidence previous features that justify the software confidence and also its correlation with state-of-the art models.

3.2.1 Crowd Control Trainer

Crowd Control Trainer is a simulator solution to train people who work with crowd-related incidents and mass events. The software was developed by VSTEP[3], an ISO9001:2008[4] certified company, in cooperation with the Rotterdam Police and the Dutch Government. This partnership was firmed in order to attend their police commanders and crowd control training managers. In

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[3] `vstepsimulation.com`.

[4] `iso.org/iso/catalogue_detail?csnumber=46486`

addition, the software was selected by the government of The Netherlands as one of the best in the field of safety and security enhancement.

The simulation takes place in a realistic virtual 3D replica of the actual urban environment allowing instant recognition and realistic planning of an actual management and response strategy for demonstrations and riots. Moreover, the software includes movement algorithms and artificial intelligence in order to compute movement of crowds of any size through the virtual training environment. Some different views of results provided by the software are illustrated in Figure 3.1.

Figure 3.1 – Illustrations from VSTEP - Crowd Control Trainer.

Furthermore, VSTEP - Crowd Control Trainer allows the police commanders to train in guiding crowds and demonstrations. Commanders can close off roads, place different kinds of barriers in the environment and instantly witness the effect these decisions have on the movement of the crowd. To prevent mass events getting out of hand, the Crowd Control Trainer allows simulation and training of riot prevention strategy. Commanders can introduce special police forces, vehicles and mounted police into the scenario in an attempt to restore and maintain order and instantly see the effects their actions have on crowd movement and behavior.

3.2.2 MassMotion

MassMotion, developed by Oasys Software [5], is designed for the creation and execution of large scale 3D crowd simulations. The company have worked in MassMotion along last ten years. The software started as a pedestrian movement simulator and has evolved into an evacuation package.

The simulator operates on a full 3D model environment. Each individual agent is made aware of their environment through bit map representations of free and obstructed space on all walkable area. Each agent determines their best available target location for the next frame of the simulation and adjusts their velocity and orientation to achieve that position. This calculation is executed at a rate of five frames per second of simulated time which is frequent enough to allow agents to adjust to dynamically changing conditions within the environment without encroaching on locations occupied by obstructions or other agents.

The simulation is based on academic research, supported by observed crowd behavior and rendered with gaming-quality graphics. Figure 3.2 illustrates examples of visualization provided by MassMotion in different projects.

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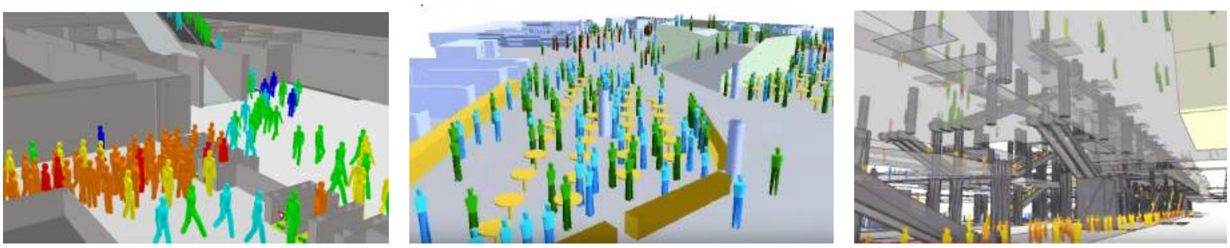
[5] `oasys-software.com`



(a) Toronto - Union Station (b) JFK - Terminal Five (c) San Francisco - Train Station

Figure 3.2 – Illustration of Results from MassMotion projects: Union Station in Toronto (a), JFK Airport (b) and San Francisco Train Station (c).

The software is also composed by an analysis tool which allows to examine, after simulations, how long it took people to get from one point to another, the flow rates for doors, stairs and escalators, and the comfort rating in different parts of the model and at various times. All this information are presented as by graphs and visuals representations. Among the applications for MassMotion, the company suggest follow areas:

- **Airport Terminal Design**: including curbside with vehicles, passenger movement and processing, baggage handling, ground side operations modeling
- **Rail and Transit**: large high density crowds and schedule based activity, neighborhood dispersion including road crossings.
- **District Modeling**: unparalleled scalability which enable the simulation of urban areas.
- **Fire and Evacuation**: Multi-floor evacuation by stairs and elevators.

3.2.3 Legion

Legion's pedestrian simulation products[6], developed in United Kingdom, include a set of tools able to deal with the simulation of pedestrian behaviors. Legion-Evac is an agent-based simulation tool where each agent can be seen to move through the environment, from an origin to a destination, weaving through the crowd and performing various activities and behaviors on the journey. It is important to mention that agents move through the environment according to the principle of least effort. In addition, random elements of behavior can be introduced to make the simulation more realistic, e.g., entity size, speed, age, and luggage. The software provides crowd simulation which can be used to assist projects with different goals. Follow, we describe the most important of them [17]:

- *Building Design*: Validate all spaces used by people
- *Operations*: Design optimal procedures for crowd event venues.

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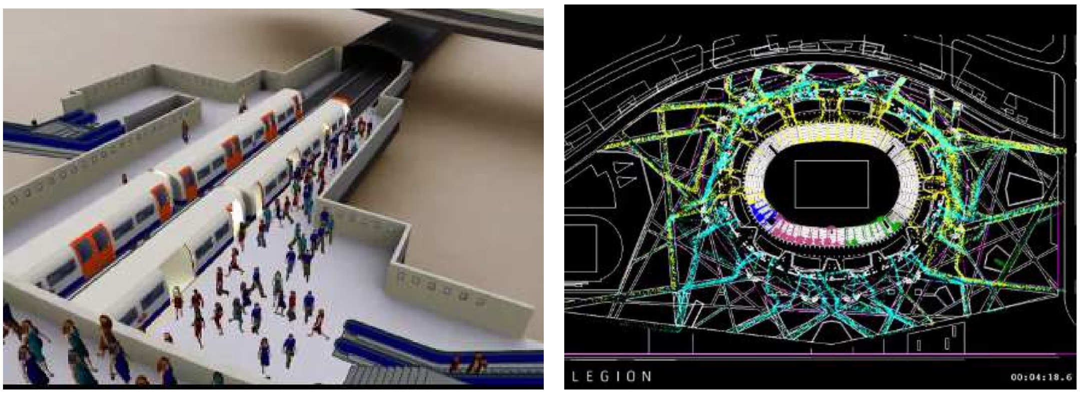
[6] `legion.com`

- *Strategic Planning*: Evaluate costs and benefits of major capital projects prior to implementation.
- *Safety and Security*: Design, test and improve evacuation procedures.
- *3D visualizations*: Demonstrate visually how a scheme would function in reality.

The company have performed, along last years, projects for different customers[7] (Figure 3.3 illustrate some of them). At this point it is important mention that one important Legion's project was developed with goal to provide simulations of Olympic sites. The Sydney Organizing Committee for the Olympic Games used Legion software to assess pedestrian circulation through the Olympic Park, in 2000. Simulation identified,among other points, unacceptably high congestion at a crucial juncture of Olympic Boulevard and prompted modifications to the design of Sydney's Olympic Park. As the best of our knowledge, Legion developed crowd simulation projects of all the Olympics games from 2000 to 2012.

(a) Airport (b) Stadium



(c) Train Station (d) Stadium Neighborhood

Figure 3.3 – Illustrations of Legion simulations: airport (a), stadium (b), train station (c) and stadium neighborhood (d).

Another option offered by Legion is the animation of realistic pedestrians and crowd movement within a 3D environment[8]. The service takes a designer's 3D model of a building or urban environment and then adds realistic animated crowds. An illustration of this facility is presented in

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[7] `legion.com/case-studies`

[8] `http://www.legion.com/news/legion-launches-3d-crowd-animation-service`

Figure 3.4. Whether it is two or 20,000 people moving through a scene, it will give clients, the public and planners an even better understanding of how a proposed development will be used and the impact it will have.

Figure 3.4 – Illustration of 3D Crowd Animation Service from Legion.

3.2.4 Comparison of Software Specifications

The National Institute of Standards and Technology, Technical Note 1680 [46, 47], provides a standardized list of features for some of the most prominent evacuation models on the market. Table 3.2 reproduces part of this review for the previous described crowd simulation software: MassMotion, VStep and Legion.

	MassMotion	**VStep**	**Legion**
Modelling Methodology	Behavioural	Behavioural	Behavioural
Purpose	Any Building Type	Any Building Type	Any Building Type
Grid / Structure	Continuous	Fine Node	Continuous
Perspective of Model / Occupant	Individual and Individual /Global	Individual	Individual
Behvaior	Artificial Intelligence / Probabilistic	Conditional / Probabilistic	Artificial Intelligence / Probabilistic
Movement	Conditional	Inter-person distance / Emptiness of Next Grid Cell	Inter-person distance / Conditional
Route Choice	Conditional	Conditional	Conditional
Validation	Codes / Drills / Literature / Other Models	Drills /Validation Against Past Experiment Literature	Codes / Drills / Validation Against Past Experiment Literature / Third PartyValidation

Table 3.2 – Features of Evacuation Models. Adapted from [46].

4. MODEL

Evacuation models may be used to highlight factors others than simply the total evacuation time. As previously discussed, the model should provide information able to extract data to be considered in safety, but also in comfort situations.

In next sections we describe *CrowdSim*, a crowd simulation software developed in order to reproduce people behavior in different situations (since normal motion until large evacuation cases). When designing *CrowdSim*, we defined some main aspects to be achieved in the software: *i)* It should be a framework easy to be used; *ii)* evacuation plans should be parametrized; *iii)* it should export various types of resulting data, that could be used later in evaluations; and *iv)* it should deal with just one agent was well as large crowds.

In addition, in order to clarify the used terminology in this work, we defined some concepts:

- navigation graph/environmental graph: it is related to a specific environment to be simulated. It considers rooms as nodes and doors and passages as edges. When the simulated environment is configured (explained later in this chapter) this graph is automatically generated;

- evacuation plan: it is an evacuation graph that contains population distribution (number of people) in the regions where agents should be created and the percentage of distribution in each bifurcation (decision point in the graph);

4.1 *CrowdSim*

CrowdSim is a rule-based crowd simulation software developed to simulate coherent motion and behaviors in an evacuation process [14, 16]. It also presents data that are used to estimate human comfort and safety in an specific environment. During the design phase of *CrowdSim*, we endeavored to develop software specifically able to:

- Represent the physical geometry of a building in a 3D environment. Such a representation allows safety engineers to use the software in order to virtually simulate an occupation or evacuation plan attending to real building physical constraints (doors, emergency exits, size of corridors).

- Define the spatial occupation of the population in the environment to reproduce initial conditions for an egress event.

- Model an egress plan in the context of emergency situations triggered by specific events over time: start evacuation, change route, etc.

- To produce a visualization of the simulation as well as to summarize data to be considered in statistical analyzes.

Two key components are considered in *CrowdSim*, organized in distinct modules: *Configuration* and *Simulation*. Figure 4.1 illustrates the software architecture including sub-modules, the necessary inputs from the user, and produced outputs.

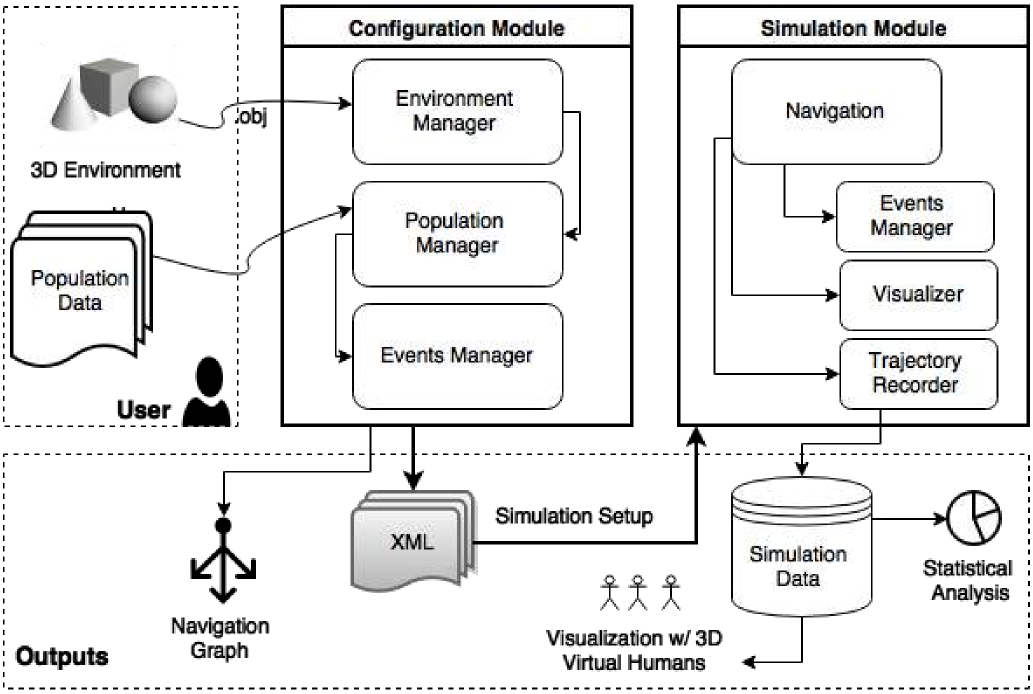


Figure 4.1 – General architecture of *CrowdSim*.

In the following sections we describe such modules of *CrowdSim* detailing their inputs, dependencies and work flow.

4.1.1 Configuration Module

The configuration module requests, as a first input, the 3D representation of the environment that will be simulated. Such a 3D model will be considered by the *Environment Manager* in order to allow the user to define the walkable regions according to the building structure as well as physical restrictions and obstacles. More specifically, the geometry components can be detailed as follows:

- **Contexts**: Regions (convex or non-convex quadrilaterals) in which agents can be created, move or be removed. It can be classified as birth, moving or goal regions, as later explained;
- **Doors**: Edges which connects two contexts and allow agents move between them;
- **Stairs and Ramps**: Regions (convex or non-convex quadrilaterals) that can connect doors from different rooms. Agents can not be created or removed in such regions; and
- **Obstacles**: Obstacles are defined into rooms in order to restrict the movement of agents within the physical environment.

When mapping the environment, the user is also able to define *population data*. In order to define the scenario that will be simulated, the *Environment Manager* classifies walkable regions with different purposes. Such walkable areas are called *contexts*. We define three different types of contexts when specifying a simulation environment: *birth*, *motion* and *goal* contexts.

Birth Contexts are used to represent areas of the building where agents should be created during the simulation. In such areas the user is requested to supply the number of agents to be simulated that should be created in such context. Also the user defines the following information based on the total number of agents to be created:

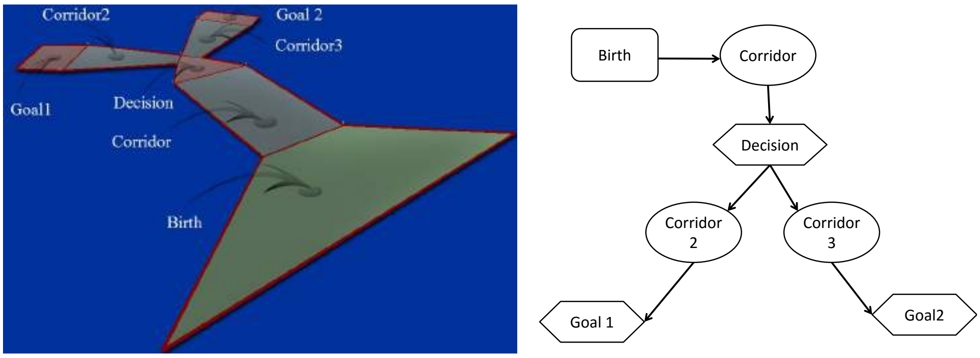
- *Groups Size*: The agents can be created in different groups until they reach the total number that should be created in the context;
- *Creation Time*: Time that groups of agents start to be created after the beginning of the simulation;
- *Time among groups*: Interval of time to be taken into account when creating different groups; and
- *Goal*: The context (or set of possible contexts) to be considered as goals to be reached by an agent when moving.

Goal Contexts are regions of interest to be considered during agent motion (goals). When creating a goal context, the user is requested to define the percentage of agents that should be removed from the simulation when achieving the context, the percentage of agents that should stay moving in such a context, and the percentage of agents that should find another goal and move in that new direction.

The *Motion Contexts* are considered by the simulation algorithm as connection regions between birth and goal contexts. They are important when calculating the agents' motion routes. In addition, a connection graph is built as an output of the configuration module according to connections among contexts and their population specifications. Such contexts allow us to reproduce a simple virtual environment, as illustrated in Fig. 4.2(a). This is just a simple example in order to illustrate an environment configuration in *CrowdSim*. In addition, this simple environment allow us to easily represent an environmental graph computed by *CrowdSim* as illustrated in Figure 4.2(b).

- A *birth context* called birth;
- three *motion contexts* called corridor, corridor2 and corridor3; and
- finally three goal contexts: *decision*, *goal1* and *goal2*.

Associated to this navigation graph, there is also a navigation mesh composed of the polygons which describe the regions in the environment. Based on these meshes, vertices are calculated



(a) (b)

Figure 4.2 – Simple simulation environment composed by different kinds of contexts (a) and its respective navigation graph computed by *CrowdSim* (different shapes in the graph mean contexts with different purposes).

(center of each polygon and the center of each edge - which represents the doors). This information together with polygons describe the regions and possible paths for all agents.

When the environment is coherently mapped and the user has defined all the *population data*, it is possible to specify in the sub-module *Population Manager* how agents should behave when moving. Agent behaviors can be:

- *Goal Seeking*: The agents should seek their goals immediately or vaguely, by performing random motion;
- *Keep waiting*: The agents, when achieving some specific region of the environment, can spend some time in it before looking for another goal;
- *Perform random motion*: The agents can chose random destinations during a specific time, before trying to identify the best path to achieve the main goal.

In *CrowdSim* we can set up two different categories of behaviors *static* and *dynamic*. Static behaviors are always performed as defined by the environment and population manager specifications. On the other hand, dynamic behaviors can be configured in the same way, but these behaviors will be performed just when a trigger is reached. Thus, the responsibility of the *Event Manager* sub-module is to define triggers to perform a series of specific behaviors. An event trigger is composed of the time to occur, a set of dynamic behaviors to be performed at that time, and a time interval between event occurrences. When a dynamic behavior is performed it is possible to set new values to agents attributes, e.g. goals and speed, in order to reproduce the desired behavior.

The correct definition of scenarios is critical in this work, because the combination and analyzes of information is responsible for producing acceptable and valid results. When the environment is totally verified with all walkable regions defined, all the parameters configured, and desired behaviors specified, the user is able to run the second module of *CrowdSim*: Simulation. The data transfer between configuration and simulation modules is currently performed by a scenario file (XML), able to store all the configurations to be observed when computing a new simulation. In addition to the XML file, the Configuration Module also generates a navigation graph with the initial distributed population in the nodes. We implemented a planner that runs offline from *CrowdSim* to read the graph and generate evacuation plans. The main difference between a navigation plan and an evacuation plan is that in the former we know where people start and in the latter we define the distribution of people at any graph bifurcation, i.e. we define the exits for each people/group. Of course, we adopt the important hypothesis that the shortest path is not always the best for crowd simulation.

Next section describes characteristics of the Simulation Module.

4.1.2 Simulation Module

The simulation module of *CrowdSim* is responsible for computing the navigation of virtual agents in a specific environment. Such navigation should coherently take into account agent motion, collision control, speed variation, and other pedestrian behaviors. A simulation setup, previously defined in the configuration module, is requested as input to the simulation. The simulation computes the routes of each agent to achieve a specific goal, based on the possible paths, as mentioned in last section. Routes can be computed based on user specification (i.e., a graph determined by the user) or computed by the best paths considering only distance criteria. *CrowdSim* uses A* [33] in order to compute shortest paths and paths free-of-collisions, if obstacles are declared. During motion simulation, *CrowdSim* avoids collisions among agents using a simple local geometry method.

The method for collision avoidance is rule-based and local defined (based on distance proximity). Close agents and their speeds are used in the collision-test to detect a possible collision situation in a next frame. If this situation is going to happen, one of the involved agents (randomly defined) must take a decision: *i)* to change its direction vector (shifts of $+-40\deg$ are allowed) as a function of goal vector, or *ii)* to reduce its speed. The information about the pair of agents and the decision taken is saved in a list of past actions, which is lost each second. If a new collision situation is detected for the same pair of agents and there is still an action in the list of past actions, the agent takes a different decision, i.e. if direction changing is saved in past actions, then a speed changing should be performed. Consequently, agents try to reach their goal, avoiding collisions with others. This method is not free-of-collision, but maximum error of 10% have been observed in all experiments performed with *CrowdSim*.

The output of each simulation contains the following information:

- Agent trajectories during the simulation;

- speed variation for each agent;

- agent simulation time;

- total time of simulation, and

- local density per time step – we compute the local density by counting the number of agents per square meter in each context, rather than the global density (i.e., number of people divided by the building area).

The output data is stored and can be used to produce different statistical analyzes. Agent trajectories can be easily exported to be visualized with articulated virtual humans in an engine that provides realistic visualization.

4.2 Heterogeneous Agents

An important aspect in crowd behaviors is how individual factors can influence on crowd evolution/simulation. For instance: can the crowd be affected when its members or part of them are not in their perfect physical or mental state? The important question in the context of crowd simulation is to know when individualism are relevant to be considered in a simulation, since the simulation of heterogeneous crowds (if compared to homogeneous crowds) obviously includes complexities to be dealt with.

As observed in this text, original *CrowdSim* deals only with homogeneous crowds, i.e. every agent has exactly the same reaction: to follow the pre-defined path (chosen by the short path or a defined evacuation plan) to evacuate the environment. In this section, we describe an extension of *CrowdSim*, in order to include heterogeneous agents. More specifically, the motivation was to simulate the influence of alcohol, or other drugs, on individual behavior. One of the few studies developed in order to simulate people under alcohol influence was developed by Moore et al. [1]. The authors consider the hypothesis that when under alcohol influence people can perform different behaviors including violent and aggressive actions. A particle model was implemented in order to validate such hypothesis. According to the authors, under alcohol influence people can be aggressive when concentrated in small places. On the other hand, Moore also reaffirms features that people perform in usual conditions (without alcohol influence): self-organization, work in lanes, less effort.

In this work, we investigate how differences in individual behaviors can influence the crowd. Inspired on available literature (World Health Organization) we simulate the behavior of agents affected by alcohol in a nightclub, as discussed in Section 6.2. Since we intended to deal with heterogeneous crowds, we included this possibility in *CrowdSim*. Mainly focused on a nightclub simulation, we chose to investigate the impact of alcohol on agents' behaviors. Table 4.1 mentions some effects of alcohol on measured by the Blood Alcohol Concentration (BAC) on the body [80]. We included just some of the effects described in the original table because many of them could not be considered in our simulations, e.g. "Decrease in various brain center functions". We implemented an individual attribute in the *CrowdSim* agents called "*goals persistence*", which is related with a factor that represents how much the agents seek goals during the simulation (i.e. related with decreased attention and slowed reactions effects). The method presents a relationship among the main characteristics of each BAC [80] level (now each agent k is initialized with a BAC value - BAC_k) and the agent goal persistence ($0 <= gp_k <= 1$).

Goals persistence of agent k is defined through:

$$gp_k = \alpha \times e^{(-\beta \times BAC_k)}, \tag{4.1}$$

where $\alpha = 1$, i.e. the value of goal persistence when $BAC_k = 0$. $\beta = 7.44$ and represents a decay constant. We chosen an exponential curve to represent gp_k due to the textual description of alcohol effects, that clearly does not represent a linear function. Based on gp_k we compute directly how many frames from next f frames that agent k should seek the goal: $nf_k = gp_k \times f$. It means that in next nf_k from f frames, agent k is going to seek the goal, so in the remaining $f - nf_k$ agent k is going to vague randomly. Results obtained with this model are going to be discussed in Section 6.2.

BAC (g/100ml)	Effects on the body (partially from [80])
$<$ 0.01	Nothing
0.01 - 0.05	Inconsistent effects on behavioral task performances
0.06 - 0.10	Decreased attention, slowed reactions, impaired coordination,
0.10 - 0.15	Dramatic slowing of reactions, impairment of balance and movement
0.16 - 0.29	Several sensory and motor impairment
0.30 - 0.39	Non-responsive stupor, loss of consciousness, death
$>$ 0.39	reduced muscle strength, reduced ability to make rational decisions Unconsciousness, death

Table 4.1 – Partially used table from [80]

4.3 Evacuation Plans Generation and Validation

Evacuation Plans are not useful just for fire situations. These plans can be easily employed in other occasions that can require evacuation. Such occasions can include severe weather problems, medical emergencies, bomb threats among others. Usually, when analyzing a specific environment, it is possible to identify different ways to leave a specific place. Normally, public places that can receive more than a certain number of people simultaneously must present an egress plan, which is defined based on safety rules and in general, not based on simulations. This section presents our approach to generate and evaluate automatically evacuation plans.

We know that many works in literature [13] describe the egress plan as a more complete structure, which takes into account the knowledge of population who lives/works in the space, the illumination, the wayfinding for non-familiar population, among many other variables. In this work, the different routes generated by *CrowdSim*, together with the population distribution in the birth contexts, as explained in Section 4.1.1 are used definition of evacuation plans. Afterward, we used an external script that reads *CrowdSim* output (XML file) and generates all the possible evacuation plans given a certain granularity of people percentage in the bifurcations. For example, if a certain environment to be simulated has 3 bifurcations and one selected distribution variation with granularity of 10%, $11^3 = 1331$ plans are going to be generated. These plans can be executed in the Simulation Module, in batch, and their results are saved in different files for posterior analysis (please, see Section 4.4.2 for extra details).

Despite that, it is a challenge to identify, among many possible evacuation plans, the one which can better serve the purpose of guiding people to the exit in a safe and comfortable way. There is no warranty that a short path can be the best one to be followed during an egress process or still that the plan with lower evacuation time is the best one. In order to evaluate different evacuation plans for a specific building, we develop a module in *CrowdSim* able to evaluate a set of simulated evacuation plans.

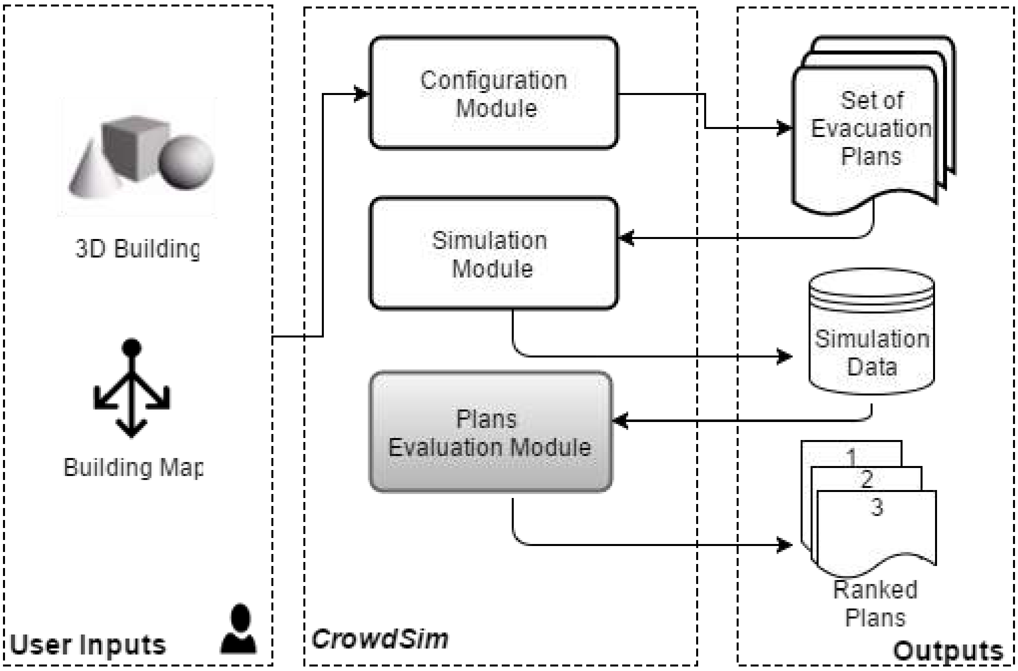


Figure 4.3 – General process of Evacuation Plans Evaluation on *CrowdSim*.

Figure 4.3 illustrates the pipeline of plans generation and evaluation on *CrowdSim*. Since an environment is mapped into a 3D world by the user, it is possible to generate the environmental graph meaning all connections among the environment areas. Follow, after the set of N evacuation plans is generated, it is necessary to simulate and collect results from all of them. It is important to note that all evacuation plans that must be compared in the same environment should include the same number of agents A, otherwise results are not comparable. Results of every simulated plan are computed and organized in a $4d$ vector for each one of evacuation plans $\vec{EP}_i$:

$$\vec{EP}_i(gt_i, at_i, ad_i, as_i) = (gt_i, \frac{\sum_{k=1}^{A} lt_k}{A}, \frac{\sum_{k=1}^{A} ld_k}{A}, \frac{\sum_{k=1}^{A} ms_k}{A}), \tag{4.2}$$

where gt_i is the total time of evacuation for evacuation plan i, i.e. the time that the last agent has left from the environment, while at_i is related with the average time needed for all agents to escape from the place (lt_k is the local time achieved by each agent k). ad_i is the average density occupied by all agents, while ld_k is the local density computed for each agent k. ld_k is computed considering agent k in the center of a $1m^2$ region where number of agents are counted. In addition the average speed as_i is also computed based on mean speed ms for each agent k. Other parameters could be also be used (examples of other parameters are illustrated in Table 6.4), however we empirically defined the most important to used in the automatic evaluation of evacuation plans.

In order to compute correctly the plan evaluation we propose to include someway the complexity of environment. So, we propose to use an agent reference in order to normalize some of evaluation parameters: $\vec{ar}(lt_{ar}, ms_{ar})$, where lt_{ar} and ms_{ar} are local time and mean speed, respectively, for a specific agent when it is simulated alone, in the environment. The proposed normalization is detailed in equations:

$$gt_i' = \frac{gt_i}{lt_{ar}}, \tag{4.3}$$

$$at_i' = \frac{at_i}{lt_{ar}}, \tag{4.4}$$

$$as_i' = \exp\left(\frac{1}{\frac{as_i}{ms_{ar}}}\right). \tag{4.5}$$

Then, evacuation plan i can be evaluated based on harmonic mean of evaluation parameters:

$$ep_i = \frac{4}{\frac{1}{gt_i'} + \frac{1}{at_i'} + \frac{1}{ad_i} + \frac{1}{as_i'}}. \tag{4.6}$$

Consequently, we are able to rank all the simulated plans and the best evaluated $\vec{EP}_j$ has $j = ARGMIN(ep_i)$ for $1 < i < N$. In order to see if this equation was coherent with real life, we contacted an expert on the domain of safety engineering. We showed him the data generated when 9 different evacuation plans were simulated and we asked him to order them. From 0 to 8, he should ordered from the worst to the best case. We just showed the resultant values, i.e. our evaluation parameters, as showed in Table 4.2.

Evacuation Plan (EP_i)	ad_i	as_i	at_i	gt_i
EP_0	0.057	0.7934	1008.28	1777
EP_1	0.06	0.7934	1002.88	1825
EP_2	2.3	0.9	1045.3	1849
EP_3	0.1	0.4	1001.66	1921
EP_4	0.068	0.7934	1018.28	1777
EP_5	0.064	0.7934	1002.88	1825
EP_6	0.062	0.7934	997.8	1873
EP_7	0.068	0.7934	1045.3	1849
EP_8	0.062	0.7934	1020.66	1921

Table 4.2 – Simulation cases from 9 different evacuation plans.

Figure 4.4 shows the ordered simulations from expert and based on our method. We can note a small difference what means a good compromise between numerical results and the quality assessment of results. Further investigations should bring new answers from experts.

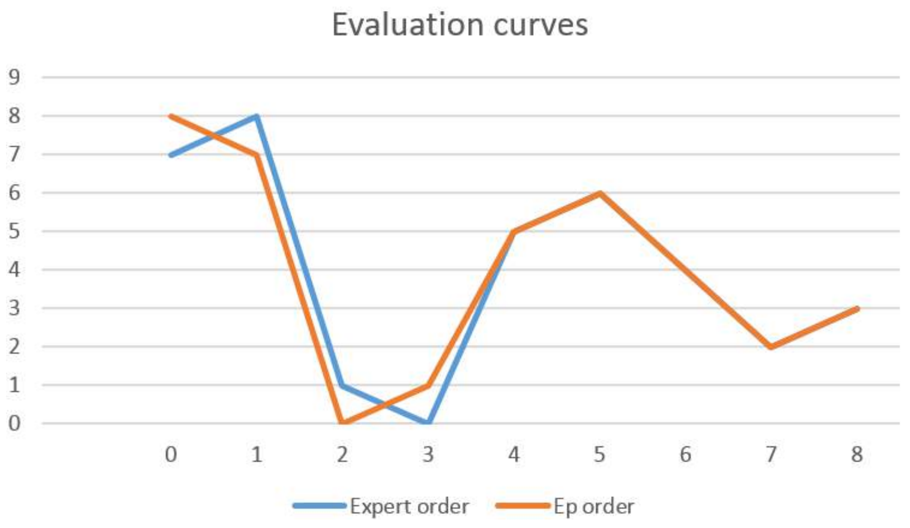


Figure 4.4 – Ordered values for each evacuation plan define by the expert and computed by our method. X axis is related with id of simulated evacuation plan while Y axis specifies the order defined by expert and the method.

4.4 Prototypes

Besides the construction and evaluation of simulation models, an important contribution of the researchers in recent years is the development of tools that allow users to interact with the scenario in order to get trained for emergency situations. These tools frequently use game engines and/or gamification techniques to make the training interactive and more engaging. Our work also aims to contribute in this area. The next sections present the prototype of *CrowdSim* and external tools that communicate with the software.

4.4.1 *CrowdSim*: Configuration and Simulation Modules

The use of graphical interfaces facilitates for the user the definition and execution of a simulation. By this way, we developed two prototypes in order to facilitates the user work on *CrowdSim*. Both prototypes were developed in C++ and OpenGL[1] supported by Irrlicht Graphic Engine[2].

In both prototypes, we implemented two types of camera: we work with orbital camera (default), but the user can change to a FPS-Style, camera. This option allows the user to access some very specific areas on the model in order to check details of the configuration/simulation.

In the configuration module, the user is available to setup all the characteristics and constraints to be taken into account when computing a simulation. On the other hand, simulation prototype allows to user to load a configuration file (XML) and compute a simulation. A graphical visualization is provided and statistical data is computed.

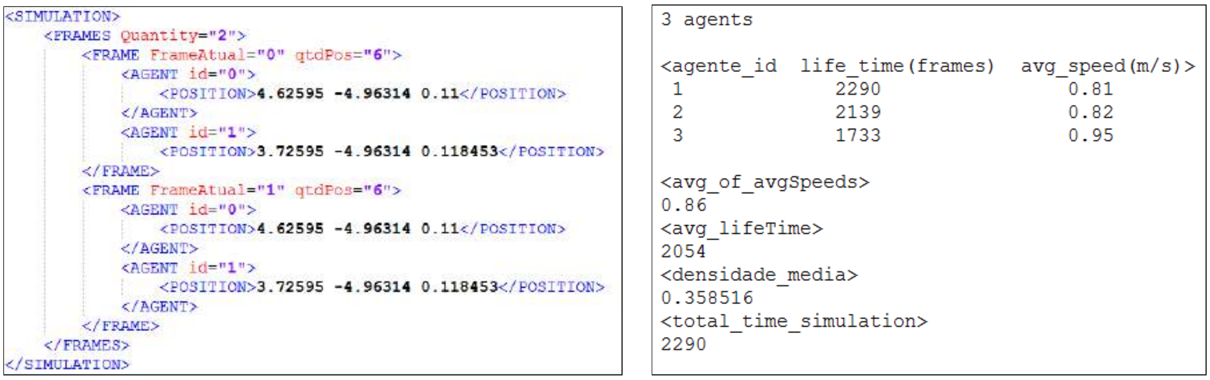
As output of this prototype we generate a file containing the agents position along the time. When we decide to export agents' log position, we can choose between two options:

---

[1] `opengl.org/`

[2] `irrlicht.sourceforge.net`

1. To record agents' positions from the beginning to the end of the simulation.
2. To record position just after some point of the simulation. In order to attend this option, the user is able, on he interface, to specify the time (in seconds) to start recording.



```
<SIMULATION>
    <FRAMES Quantity="2">
        <FRAME FrameAtual="0" qtdPos="6">
            <AGENT id="0">
                <POSITION>4.62595 -4.96314 0.11</POSITION>
            </AGENT>
            <AGENT id="1">
                <POSITION>3.72595 -4.96314 0.118453</POSITION>
        </FRAME>
        <FRAME FrameAtual="1" qtdPos="6">
            <AGENT id="0">
                <POSITION>4.62595 -4.96314 0.11</POSITION>
            </AGENT>
            <AGENT id="1">
                <POSITION>3.72595 -4.96314 0.118453</POSITION>
            </AGENT>
        </FRAME>
    </FRAMES>
</SIMULATION>
```

(a)

```
3 agents

<agente_id  life_time(frames)  avg_speed(m/s)>
 1              2290               0.81
 2              2139               0.82
 3              1733               0.95

<avg_of_avgSpeeds>
0.86
<avg_lifeTime>
2054
<densidade_media>
0.358516
<total_time_simulation>
2290
```

(b)

Figure 4.5 – Example of Position and Summary files produced by our prototypes.

4.4.2 Evacuation Plans Generation, Simulation and Analyzes

In order to make easier the simulations computing and analyzes, we developed three different scripts that communicate with *CrowdSim* in order to facilitate our work. We created two python[3] scripts and one C++ program that are follow described:

1. *generatePlans.py*: Receive as input a XML file, defined in *CrowdSim* (see Appendix A for an exemple file) configuration module, representing an environmental graph. Follow, according as a specified granularity, generate all the possible evacuation plans for such environment.
2. *simulatePlans.py*: Script responsible by simulating a set of evacuation plans (XML files generated by the script *generatePlans.py*). As input, we specify just the folder where the XML files are located. The script are able to run the simulation module of *CrowdSim* for each evacuation plan in the folder. The results of this process is a summary file containing simulation details for each plan (see Fig 4.5(b) for a summary sample).
3. *evaluatePans.cpp*: A C++ solution developed with goal to compute all the simulation summaries in order to rank them. The program receive as input the directory where simulation summaries are located. In addition, it is responsible for reading such information in order to compute the ep value as previously presented in Section 4.3. As output, the program export a rank with all the evaluated plans detailing values of ep, density, speed and time as well.

---

[3] python.org

4.4.3 3D Visualization

We developed a 3D visualization prototype in order to visualize our results using animated virtual humans. Developed with Unity 3D[4] the prototype receive as input a trajectories file as the one exemplified in Figure 4.5(a).

The prototype loads all the trajectories and allow to user:

1. To select a 3D model to be used as the simulation scenario. This option is non-mandatory, in order the user decides to just observe the trajectories on the 3D environment.
2. To visualize the trajectories of all the simulation or, on the other hand, to verify the trajectories evolution along the time.
3. To include 3D humans which will walk according to the trajectories.
4. To verify the heat maps computed based on the trajectories evolution along the time.

Results obtained with this prototype can be verified along the text. In addition, it is used in order to render all the images including virtual humans presented in Chapter 5. One example of obtained heat map is illustrated in Figure 4.6.

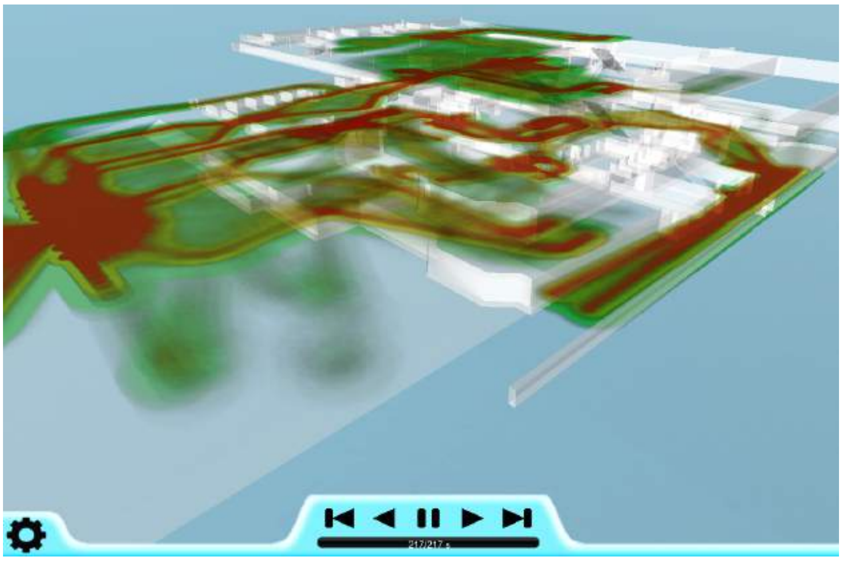


Figure 4.6 – Example of visualized heat map.

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[4] `unity3d.com`

5. *CROWDSIM* VALIDATION

Nowadays we can observe the increase of the simulators usage in order to provide data in evacuation where real world training wold be difficult, uncomfortable, dangerous and also have ethical implications. Also when in fire drills, building occupants typically exit at a leisurely pace, without having to deal with panic inducing events such as smoke filled corridors, fires in unexpected places or blocked fire exits [65]. In order to compute coherent data aiming to reproduce real life behavior in evacuation, it is very important to validate the accuracy of the employed simulator.

Based on software engineering literature, *Validation & Verification* can be considered as one of the most important software development activities [2, 5]. The purpose is to guarantee that the software was correctly built. In this chapter we present how the validation process was performed in *CrowdSim*. We assume as *validation*, for this thesis, the systematic comparison of *CrowdSim* predictions with reliable information.

The validation of crowd simulators have been addressed in different scientific approaches.The work of [46] presents a set of guidelines to be observed as general requirements of crowd modeling on simulation software. The authors attempted to aid users in the selection of an appropriate evacuation model by identifying key factors and explanations regarding project requirements, the background of the model, the current capabilities and characteristics of the model for comparison with other models, and the future progress of a model for a specific application. Furthermore, the authors observe that besides knowing the software, it is necessary to have knowledge in crowd behavior. In this thesis, we adopt the following concepts for:

- **Validation**: The computational model is able to provide an acceptable representation of "real life" evacuation situations; and
- **Verification**: Verify that the theoretical definitions of the model were coherently implemented.

The work of Ronchi [68] stated that evacuation models are increasing in complexity as the understanding of human behavior in fire progresses, but there is a lack of understanding regarding evacuation model user experiences and needs. In order to find out the desired needs of the evacuation modeling community, an online survey was developed with participants from 36 different countries. Results have shown that model users consider validation/verification as the most important factor when defining the model to use.

Haron *et al.* described the evaluation process carried out to determine the most suitable software for the purpose of studying the evacuation process of Al-Masjid An-Nabawi in [32]. The authors compare the cost-benefit relationship of three off-the-shelf software systems. In order to validate egress systems, as a software, the work of Galea [27] presents a set of different validations to be performed. According to the author there are at least four forms of validation/testing that evacuation models should undergo:

1. *Component Testing* involves checking that the various components of the software perform as desired. This involves running the software through a battery of elementary test scenarios to ensure that the major sub-components of the model are functioning as intended;

2. *Functional Validation* involves checking that the model possesses the ability to exhibit the range of capabilities required to perform the intended simulations. This requirement is task specific. To satisfy functional verification the model developers must set out in a comprehensible manner the complete range of model capabilities and inherent assumptions and give a guide to the correct use of these capabilities;

3. *Qualitative Validation* concerns the nature of predicted human behavior with informed expectations. While this is only a qualitative form of verification, it is nevertheless important, as it demonstrates that the behavioral capabilities built into the model are able to produce realistic behaviors; and

4. *Quantitative Validation* involves comparing model predictions with reliable data generated from evacuation demonstrations.

This four sets of tests are already recognized and considered in the field of safety engineering in order to validate evacuation systems[1]. In London, the International Maritime Organization (IMO) developed *guidelines for evacuation analysis for new and existing passengers ships* IMO [41] based on Galea's work. The goal is to validate and verify tools able to simulate an evacuation process. Such guide aims is to develop a methodology for conducting an advanced evacuation analysis in order to built systems coherently able to:

- identify and eliminate congestion regions which may arise during an abandonment, due to normal movement of passengers and crew along escape routes, taking into account the possibility that crew may need to move along these routes in a direction opposite to the movement of passengers;

- demonstrate that escape arrangements are sufficiently flexible to provide the possibility that certain escape routes, assembly stations, embarkation stations or survival craft may be unavailable as a result of a casualty.

In this chapter we detail the set of tests suggested by IMO in order to validate *CrowdSim*. We have decided to validate *CrowdSim* according component testing, qualitative and quantitative validation. We aim, in the future, to investigate the best way in order to validate our software according to functional requirements. Next sections explain about performed tests for each category.

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[1] This procedure has been highlighted in ISO document ISO/TR 13387-8:1999.

5.1 Component Testing

Component testing is part of the normal development cycle and involves checking if the various components of the software perform as intended. This involves running the software through a battery of elementary test scenarios. In the following, we present a list of adopted component tests extracted from [41] and applied in *CrowdSim*.

5.1.1 Maintaining set walking speed on a Corridor

The first component test defined on IMO's guidelines validates the speed of a single agent when moving in a specific known environment. We built a $2m$ wide and and $10m$ long corridor (illustrated in Figure 5.1) and simulated one agent walking from left to right with speed of 1 m/s. The success criteria of this test assumes that the agent should walk 10 meters in 10 seconds.

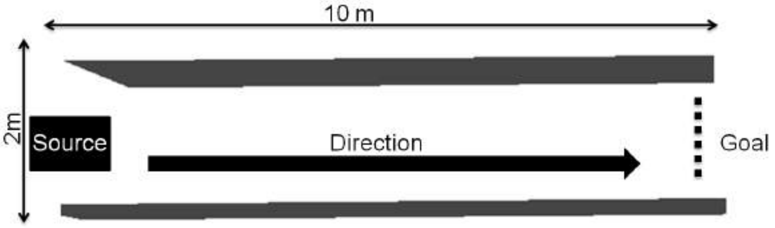


Figure 5.1 – Environment of walking speed test

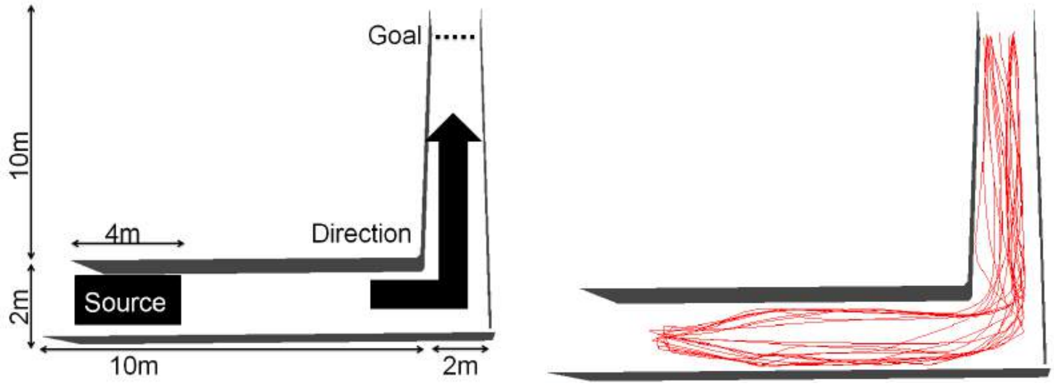
After ten individual simulations we compute acceptable average values (presented in Table 5.1). The obtained average individual speed was $1.08m/s$ with standard deviation of 0.09m/s. The average walked distance was $10.232m$ (standard deviation of 0.097m) and time of $9.506s$ (standard deviation 0.769s). According to IMO's specifications we observe that *CrowdSim* successful achieves this criteria.

Agent ID	Speed (m/s)	Walked Distance (m)	Simulated Time (s)	AVG Vel (m/s)
1	0.95	10.3	10.8	0.95
2	0.99	10.28	10.16	1.01
3	1	10.05	9.84	1.02
4	1.02	10.32	983	1.04
5	1.04	10.18	9.54	1.06
6	1.07	10.15	9.16	1.10
7	1.1	10.18	9.83	1.03
8	1.11	10.19	8.83	1.15
9	1.13	10.39	8.83	1.17
10	1.2	10.23	8.16	1.25
AVG's	1.06	10.23	9.49	1.08
Standard Deviation	0.07	0.09	0.76	0.08

Table 5.1 – Summarized data after 10 simulations of corridor scenario.

5.1.2 Rounding corners

This test evaluates the agent's ability to walk around a corner without colliding with walls and other agents. We simulated twenty people approaching a left-hand corner according to specifications illustrated in Figure 5.2(a).



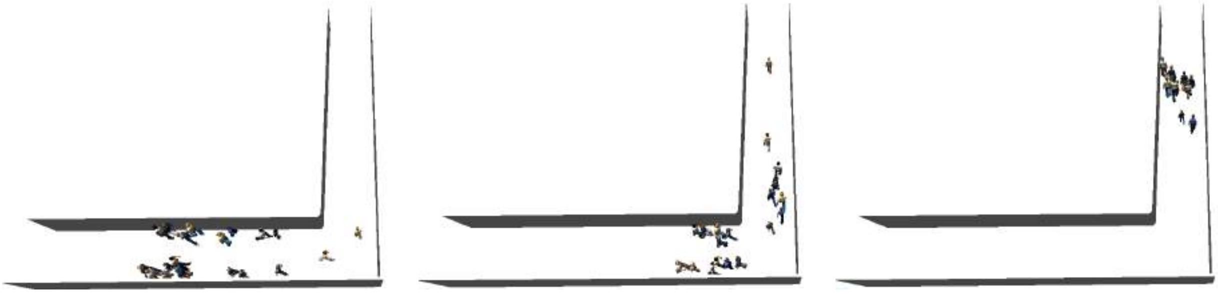
(a) (b)

Figure 5.2 – Setup of the experiment environment (a) and obtained trajectories of rounding corner simulation (b).

According to IMO's guidelines, this test aims to verify two specific points:

1. *The agents should successfully navigate around the corner without penetrating the boundaries.* Figure 5.2(b) illustrates the simulated trajectories of all twenty agents. A visual check shows that agents do not collide with the walls.

2. *The agents should successfully navigate without overlap at any time.* Figure 5.3 illustrates three situations for a typical simulation at different moments. While it is difficult to visually verify collision avoidance, we observe in the agentsÂ´ positions file (generated in the simulation) that there are no overlaps among agents (computed by their interpersonal distances).



(a) time = 10 seconds (b) time = 15 seconds (c) time = 25 seconds

Figure 5.3 – Simulation for rounding corner test.

5.2 Qualitative Validation

Qualitative Validation concerns the nature of predicted human behavior with informed expectations from observed situations. While this is only a qualitative form of verification, it is nevertheless important, as it demonstrates that the capabilities built into the model are able to produce realistic behaviors. The qualitative tests performed in order to validate the *CrowdSim* simulator are the impact of counter flow in evacuation time, crowd dissipation from a large public room, and exit route allocation. These tests are described in next paragraphs.

5.2.1 Counter flow - impact in evacuation time in two rooms connected via a corridor

This test was performed according to the environment illustrated in Figure 5.4 populated by 100 individuals. The test was implemented in two steps described as follows:

1. Agents move from room 1 to room 2, where the initial distribution is such that the space of room 1 is filled from the left with maximum density. The time elapsed for last person enters room 2 is recorded.

2. Step one was repeated with an additional 10, 50, and 100 people in room 2. People from both rooms move simultaneously to the other room, and the time for the last person in room 1 to enter room 2 is recorded. The expected result is that the recorded time increases as the number of people in the counter flow increases.

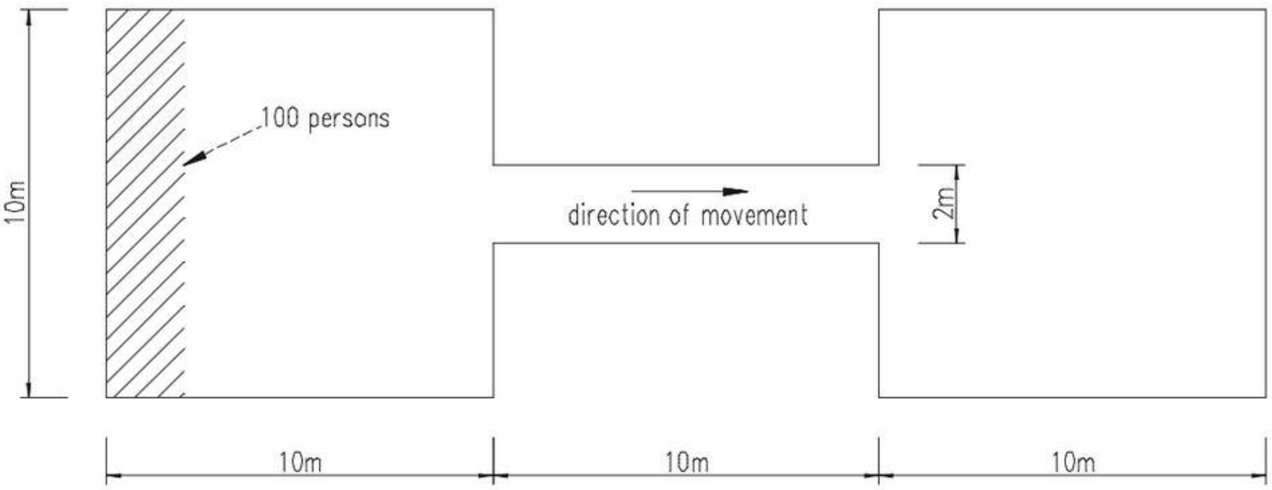


Figure 5.4 – Counterflow scenario configuration according to IMO's specifications

We repeated each of the scenarios described in steps 1 and 2 ten times, considering different seeds for the random number generator, which led to a test bank of 40 simulations. The expectation of increasing the time for evacuation of room 1 with the increasing number of agents in counter flow was observed, as shown in Figure 5.5. The graph in this figure illustrates the average time variation with the number of agents in counter flow. The black markers near to each point represent the standard deviation for the ten simulations in each case.

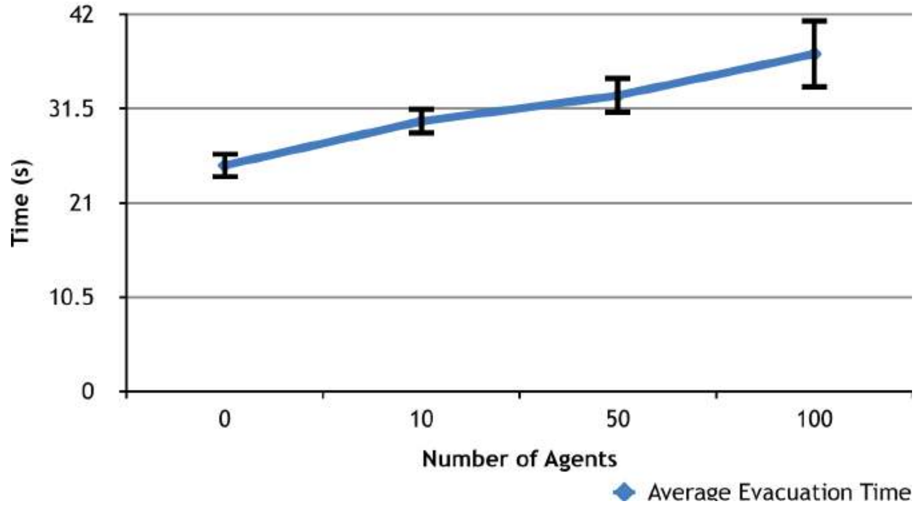


Figure 5.5 – Average and standard deviation of time for evacuation from room 1 as a function of the number of agents in counter flow.

5.2.2 Exit flow: crowd dissipation from a large public room

This test was performed in a public room populated by 1000 agents where 4 exits are available to be considered during evacuation as illustrated in Figure 5.6. According to IMO's instructions, the test should run according to two steps: first, simulate and record the time for last person that leaves the room when 4 exits are available and second, the same situation but considering doors 1 and 2 as closed.

The success criteria for this test is related to the amount of time for evacuation in the two cases. According to IMO, the elapsed time of the second case should be around 50% greater than in case 1. When such an experiment was performed with *CrowdSim*, we computed the time of $83.79s$ in the first case and 181.62s in the second. These values meet the requirement and, as a consequence, we can consider that *CrowdSim* is validated according to this criteria.

5.2.3 Exit Route Allocation

The IMO specification for this test has requested us to build a cabin corridor section populated as indicated in Figure 5.7(a). The success criteria for the test assumes that:

1. The main exit was allocated as the goal for the people from cabins 1, 2, 3, 4, 7, 8, 9, and 10.

2. The secondary exit was allocated as the goal for all the remaining passengers.

We performed such a test in *CrowdSim* where the agents move to their assigned exits. Figure 5.7(b) presents the agents' trajectories in the 3D environments illustrating the success of the test.

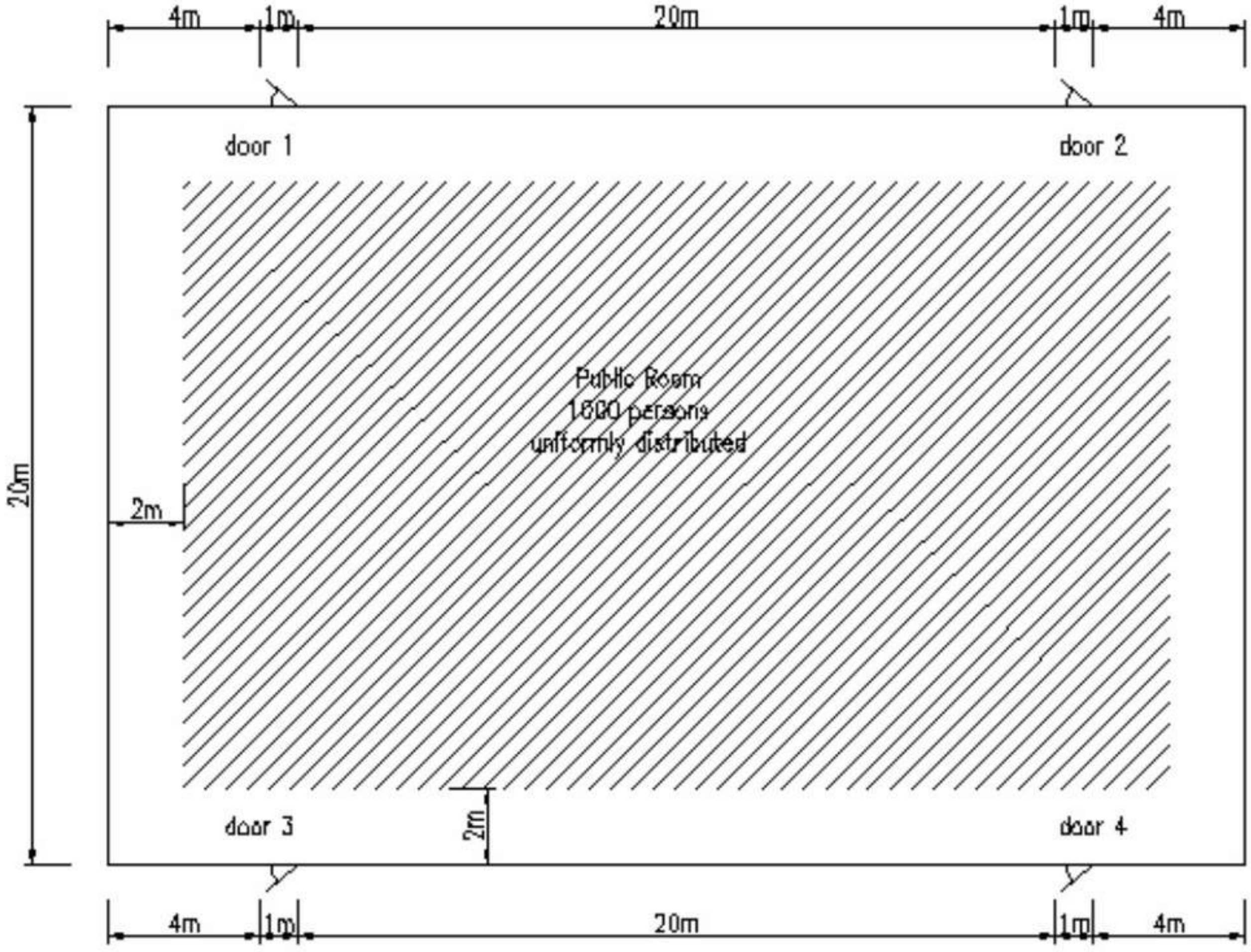


Figure 5.6 – Exit flow scenario configuration according to IMO's specifications

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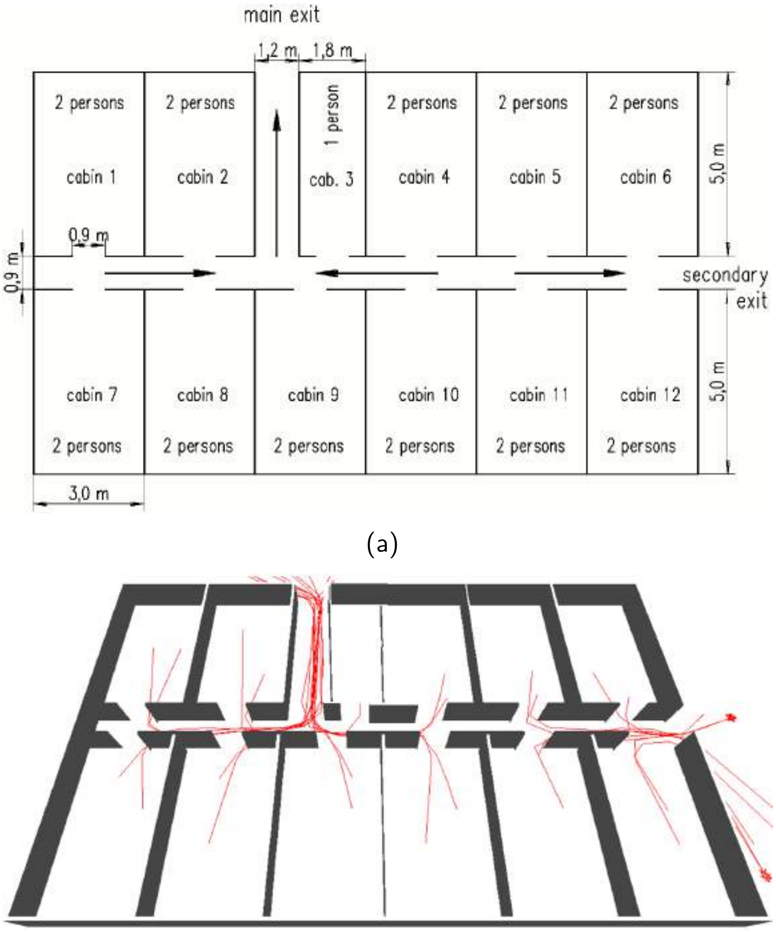
5.2.4 Staircase

This test requires to build an environment where a room (5m x 6m) is connected to a stair by a corridor (2m x 12m). Besides that, a population of 150 agents need to be created inside the room and move through the stair. The expected result is that congestion appears at the exit from the room, which produces a steady flow in the corridor with the formation of congestion at the base of the stairs. Figure 5.8 presents a heat map built according to this case specification. Based on visual inspection it is possible to observe two bottleneck regions (highlighted in the figure) which match with the success criteria.

5.3 Quantitative Verification

Quantitative verification involves comparing model predictions with reliable data generated from evacuation demonstrations. Galea's work highlights [27] two kinds of quantitative validation: *historic* and *prediction* based validation. In the first case, the user knows the results from previous simulations and real exercises. On the other hand, the second case involves using the model to perform predictive



(a)

(b)

Figure 5.7 – Exit Rout Allocation: (a) IMO specification for the test and (b) agents performed trajectories.

simulations prior to having sight of experimental results.

To the best of our knowledge, current IMO's guidelines do not have evaluated any experimental data in order to allow a thorough quantitative verification of egress models. Therefore, in this work, we propose a method to quantitatively validate *CrowdSim*.

It is important to mention that the quantitative validation should take into account other information besides the total evacuation time. Such information is based on the simulation model outputs and should include, not exclusively, data as exit selection, behavior in different conditions, bottlenecks regions, exit and finish times. On the other hand, the level and quality of quantitative validation is dependent on the completeness and quality of the reported data [27].

Wherever possible, the simulations performed by *CrowdSim* have been quantitatively evaluated. Several data analysis from simulation data have been undertaken in order to validate simulation results. For the purposes of the *CrowdSim* validation, follow we present results of performed comparisons:

- *CrowdSim* was used to simulate the evacuation of a night club that was also part of a real egress exercise [14]. In this project, we were able to record data from real life in order to contrast with

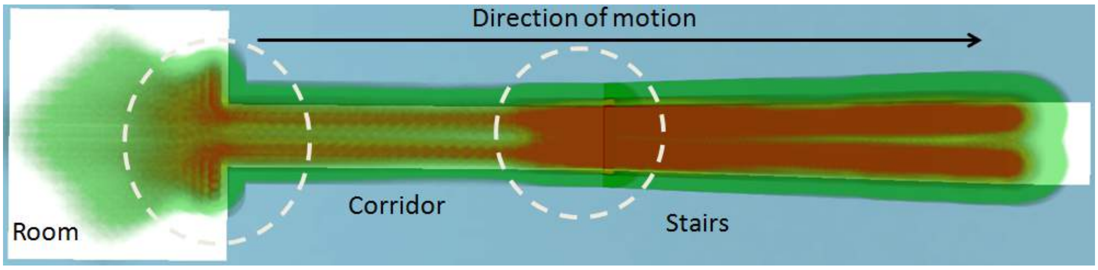


Figure 5.8 – Illustration of stair case validation. It is possible to observe success criteria at the room door as well as in front of the stairs.

CrowdSim predictions. Such recorded date includes local and global times, local and global densities and speeds (please refer to sections 6.1.5 and 6.1.3). The analysis of simulated data allowed us to verify some attention points validated during the real egress exercise: *i)* region of highest density (stairs); *ii)* we have estimated a greater density of 5.4people per sqm while in real life, the maximum value was 4.5 people by sqm. *iii)*the greater density was observed at second 40 of simulation, while second 50 during real egress exercise; *iv)* the observed times of simulation and real life were coherent.

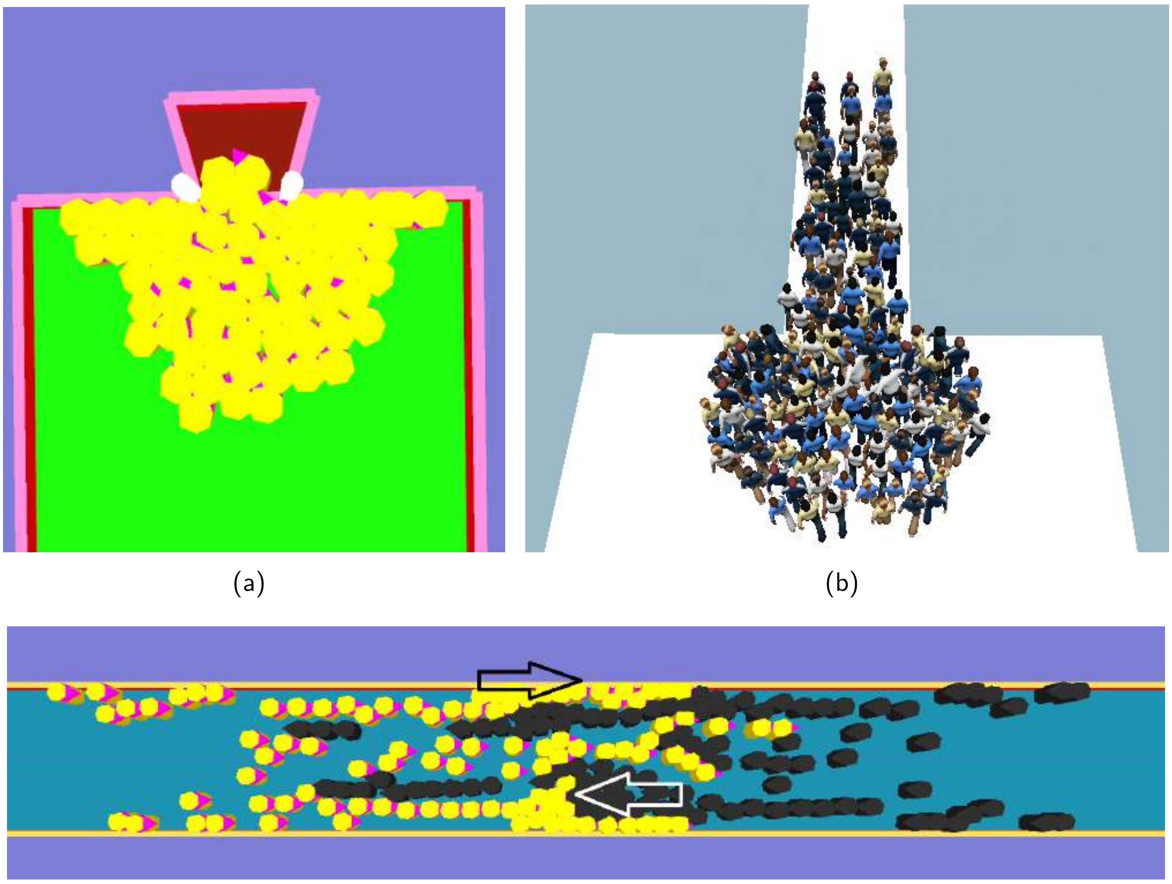
- we also applied *CrowdSim* to reproduce crowd behavior when evacuating a college building. An analyzes of the extracted data from real and simulation scenarios allows us to observe that: *i)* times observed in simulated and real scenarios, besides different, are coherent. We believe that the difference occurs because all the simulation agents were created and started to move in the exact same time, in a different way from real life, where people have different response time to events. Also real people do not feel panic voluntarily, since they know that a egress exercise is not a real fact of panic; and *ii)* The analyzes of the simulation results allows us to compute the density of the place during the simulated evacuation process and address attention points.

Without exception, we know that this process for quantitative validation is yet simple due to the lack of rich information captured during an egress event (real life or simulation). However these information were used by the managers of the night club and college building in order to improve their evacuation process. Detailed information of such projects are presented in the case studies described in next chapter.

5.4 Observing Emergent Behaviors in CrowdSim

Additionally to *CrowdSim* validation, according to IMO's scenarios, we are interested in checking the software capability in reproducing self-organization phenomena. We know, as previously explained in Section 2.1, that crowds can perform some emergent behaviors under specific circumstances.

When performing different simulations, we were able to observe that some self-organization phenomena have emerged in *CrowdSim*. Figure 5.9 illustrates such behaviors: arch formation (a), also visualized with virtual humans (b) and lane detection (c).



(a) (b)

(c)

Figure 5.9 – Emergent behaviors observed during *CrowdSim* validation: Arch formation (a) and (b) lane formation.

It is important to mention that such detected behaviors were emerged without any interference, i.e. we did not codificate any criteria or rule in order to influence such formations.

5.5 Validation Summary

In this chapter we detailed the validation process applied in *CrowdSim*. A set of tests were performed according IMO's [41] guidelines in different categories [27]. In addition, we complemented the tests indicated by IMO by defining a process that allowed to validate *CrowdSim* in a quantitative way, according to results able to be compared with real-life scenarios. This can be considered a differential of previous IMO's application on software validation. Other important aspect is related with emergent behaviors. As previously presented, some behaviors related to self-organization of crowds have emerged in our simulations, as could be observed in Section 5.4.

6. EXPERIMENTAL RESULTS

This chapter describes the results obtained with our research. Firstly, we detail a set of performed case studies in which we have applied *CrowdSim*. The main goal is to demonstrate *CrowdSim* and also to present the accuracy of the simulations. In addition, we present several experiments in order to highlight the use of CrowdSim in different circumstances involving heterogeneous agents and diverse behaviors.

At the end of this chapter, we discuss the evaluation of evacuation plans. We demonstrate a set of experiments performed and evaluated according to the metric proposed in our research (Section 4.3).

6.1 Case Studies

When analyzing an egress process simulation, it is possible to extract data that can be used to provide a deeply analysis of scenarios. Before something goes wrong, a simulation project can identify attention points related to people comfort and safety when in egress.

The data obtained by crowd simulation can be very useful to safety analysis in order to estimate environment conditions and attention points (i.e. bottlenecks regions) as well as to map and understand people behavior during an evacuation process. Although the final evacuation time is commonly the only variable used in the analysis, other information are also important. According to Galea [27], in addition to total time of evacuation, important information can be considered:

- Bottleneck regions;
- exit selection, exit flow rates, exit start and end times; and
- agents behaviors in different conditions (e.g. when under smoke and alcohol influence).

With the *thinking of safety* in mind we have applied *CrowdSim* in a set of projects which the main goal is to demonstrate its potentiality in real-world application. Each project contains a different setup, but all of them are concerned with evacuation behaviors. In each project we were able to analyze different populations and also different ways to people leave the specific building. To this, in each project we ran different simulations setups, aiming to analyze different situations. Moreover, comparing the obtained results from different simulations in the same environment, we can evaluate the efficacy of alternative evacuation strategies and also the building structure.

Next section describe the *project pipeline*, common to all performed projects.

6.1.1 Case Studies Pipeline

Despite that each case study considers different buildings and population details, all of the projects followed the same execution pipeline. Such pipeline is illustrated in Figure 6.1.

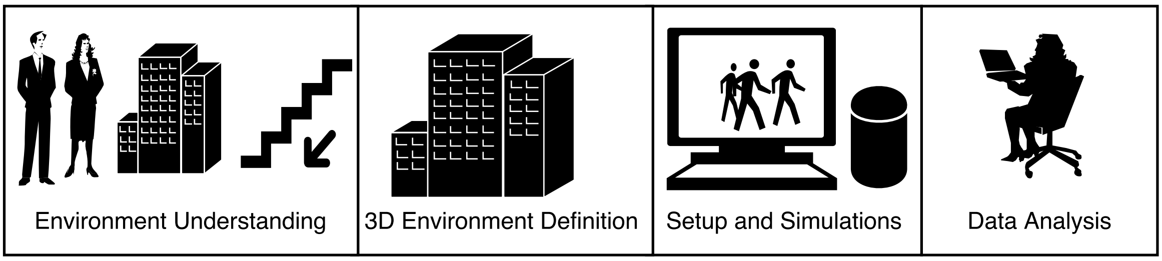


Figure 6.1 – Common pipeline of performed case studies.

During the projects development, for all case studies, we followed 4 commons steps:

1. *Environment Understanding*: A near contact with the biding manager it is very important in order to understanding all the building structure and also its functionalists. In addition, building managers also provide some valuable information about how people use to behave in such place. At this point, we try to map and understand the use of doors, corridors and more common routes which are used by people when leaving the building;

2. *3D Environment Definition*: It is necessary to reproduce the building into a 3D environment. This activity is usually performed by a graphical designer who reproduces all the building details (doors, corridors and other obstacles) in a coherent way to real world;

3. *Setup and Simulations*: We define, in the 3D environment, semantic information regarding to represent all the different regions of the place. In *CrowdSim*, we specify the contexts which detains information about the areas where people will be inserted and removed in the simulation. In addition we also map the regions where the motion of pedestrian is allowed (corridors) and population details (number of agents, their goals, etc). After, we run the simulation in order to compute data to be analyzed; and

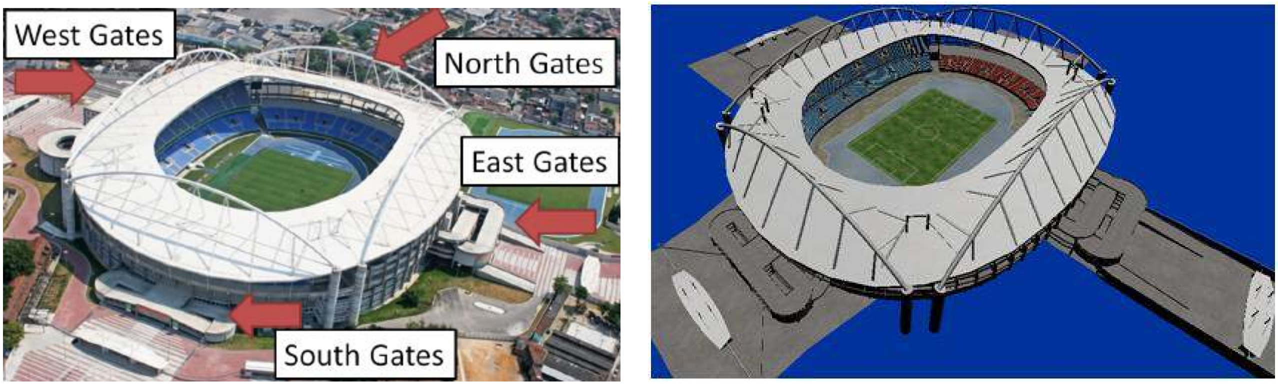
4. *Data Analysis*: After the simulations are complete, we analyze the obtained statistical data in different way. The goal is to map aspects of people comfort and safety when in egress, as well as, to map bottleneck regions and other possible attention points. In order to do this we inspect the simulation outputs in order to analyze aspects of density, agents, speed, global distribution along the time, etc. Such information is usually part of a report which is shared with all the project stakeholders.

Follow, we detail each one of the performed case studies were CrowdSim was applied.

6.1.2 Evacuation performance of a Olympic Stadium

In this case study we have applied *CrowdSim* in order to study the evacuation process of a Olympic Stadium. The Brazilian *Olympic Stadium JoÃ£o Havelange*, called *Stadium Nilton Santos* since 2010, was built for the *2007 Pan American Games* and according to the stadium managers can be considered as the most modern stadium of Latin America and number five in the world[1]. The stadium, site of Brazilian soccer team Botafogo[2], has capacity of 46,000 people. There is a project to increase it to 60,000 people in order to attend the Olympic Games in 2016. The project was performed as a partnership between PUCRS and Botafogo with the main goal to provide a study of the crowd egress process in the stadium. The factors considered in the analyzes represent information of people comfort (density of people) and also the total time of evacuation.

A representation of the stadium is illustrated in Figure 6.2. The stadium can be accessed by four distinct areas, as presented in Fig. 6.2(a). The detailed understanding of the stadium structure, i.e gates and corridors, is very important when staring a crowd simulation project. This is because the first phase in the project is concerned with the modelling of the 3D environment (a 3D representation of the stadium is illustrated in Fig. 6.2(b)).



(a) (b)

Figure 6.2 – In (a) is presented a real view of the Olympic Stadium where is highlighted the four areas of access to audience; while in (b) we illustrate a 3D representation of the stadium.

When building the 3D model of the stadium is important to take into account all the physical constraints existing in the real stadium. The doors size, corridors dimensions and the existence of obstacles should exist in 3D model. Figure 6.3 presents common areas of the stadium that were considered when developing the 3D model.

Another important aspect considered in this project was the correct specification of the grandstand areas. In Figure 6.4 it is possible to observe such areas (red floor and green chairs) and the regions defined to allow the motion of pedestrians (blue). Considering such definition, when an event occurs, e.g the end of a match, the individuals are able to leave their seats and find the best way to leave the stadium.

In this project we simulated three different situations considering information about historic of matches provided from the stadium managers:

1. The average of population during some observed matches: 17,000 people;
2. full capacity: 46,000 people; and

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[1] `http://bfr.com.br/estadioniltonsantos.php`

[2] `http://bfr.com.br`

(a) (b) (c)

Figure 6.3 – Three representations of common areas in the stadium, including grandstand and corridor regions, where people are allowed to walk.

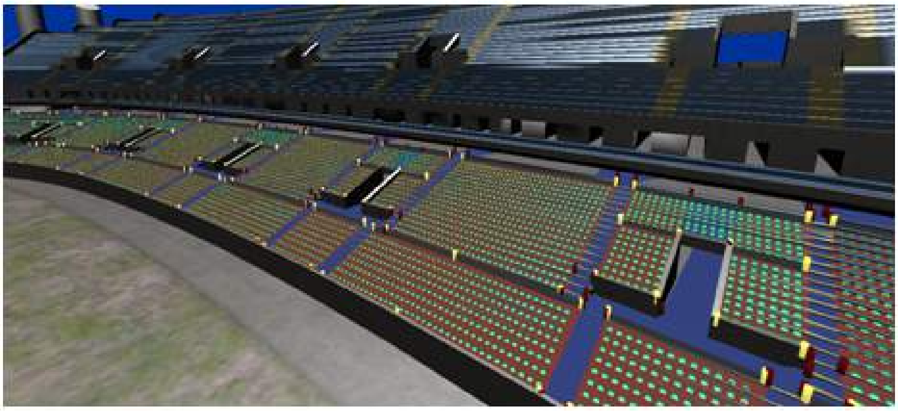


Figure 6.4 – Example of simulation configuration considering grandstand areas.

3. a test case where we considered the full capacity of the stadium together with the unavailability of one exit (see figure 6.5).

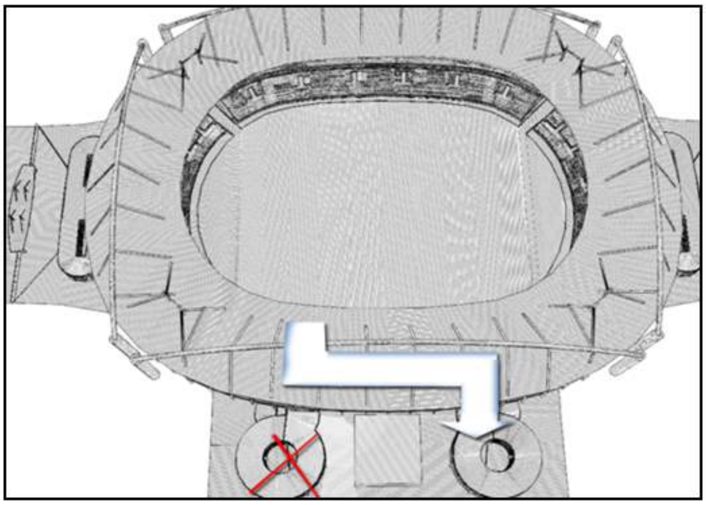
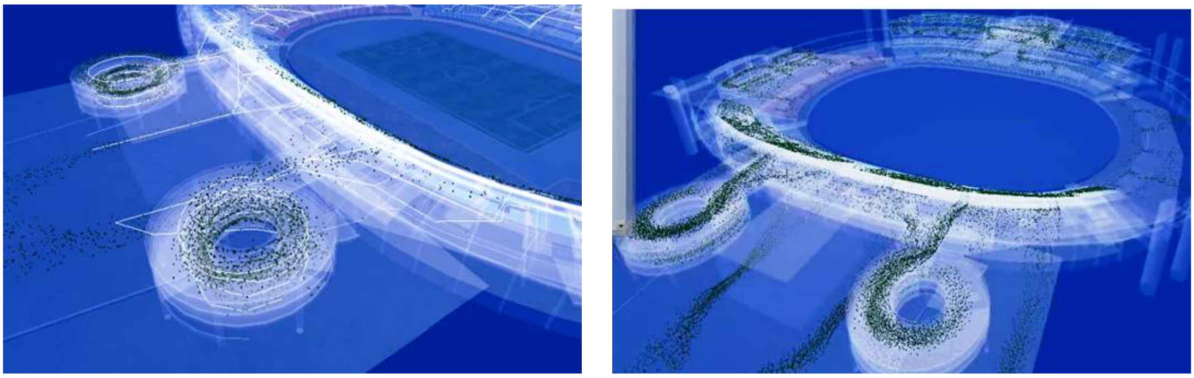


Figure 6.5 – Illustration of 1 unavailable exit in the stadium.

It is important to highlight that all agents agents know their best exit, even when one exit was closed, the agents knew that and went directly to the second best exit. After the simulations, we performed some statistical analyzes that have allowed us to highlight some points:

- In all simulated situations the agents were able to walking according close to their desired speed (1.2 m/s);
- The last item is used to consider that population can have safe egress process in simulated scenarios; and
- The average time of all scenarios was around 7 minutes.

Figure 6.6 illustrates two moments of the simulations in the stadium.



(a) Simulating zooming two of the exits. (b) Crowd evacuating the Olympic Stadium.

Figure 6.6 – Visual representation of egress performance in the stadium.

Final Considerations about this Project:

The results of this section are already published in a paper [16] and also are part of the book *Crowd Simulation* [75] - Chapter Applications: Case Studies. This project received very well attention form the media because it was a new technological application developed in Brazil. Appendix B.1 presents one of the news from Brazilian media about the project and the interest of the stadium managers about safety issues. In addition, a video case of the project is currently available[3].

6.1.3 College Building

In this case study we applied *CrowdSim* in order to reproduce pedestrian behaviors when leaving the Faculty of Informatics (FACIN) building at PUCRS[4]. The building is composed by eight floors, where it is possible to identify class rooms (floors 2, 3, 4 and 5), professors offices, research labs (floors 6 and 7) and business offices (floors 1, 7 and 8). Furthermore, there are two emergency exits that are accessed by stairs from all floors. The population of the building is around 800 people every day. This scenario is illustrated in Figure 6.7 where we can observe a real external picture of the building (a) as well as the respective 3D model (b) and the building environment represented in *CrowdSim* (c).

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[3] `https://goo.gl/f2Rud6`

[4] `www.pucrs.br/facin`

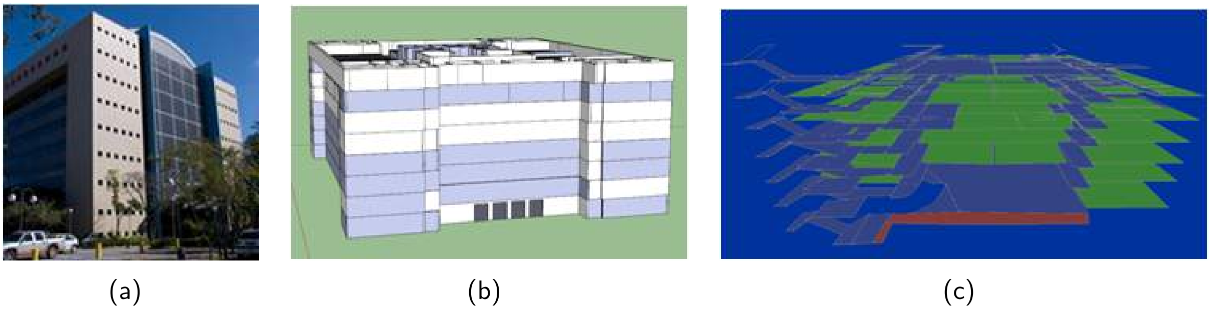


Figure 6.7 – Three representations of the building simulated in this case study: the real building (a), 3D environment (b) and simulation environment defined in *CrowdSim*.

The 3D virtual environment was modeled by an 3D artist using Google Sketch Up according to the building's floorplans. Each floor of the building is coherent with the real environment dimensions. The illustration of the first floor is presented in Figure 6.8 where the two emergency exits previously described (one in the front and other in the back of the building) are highlighted. For this case study, the furniture inside the building is not considered in the simulation.

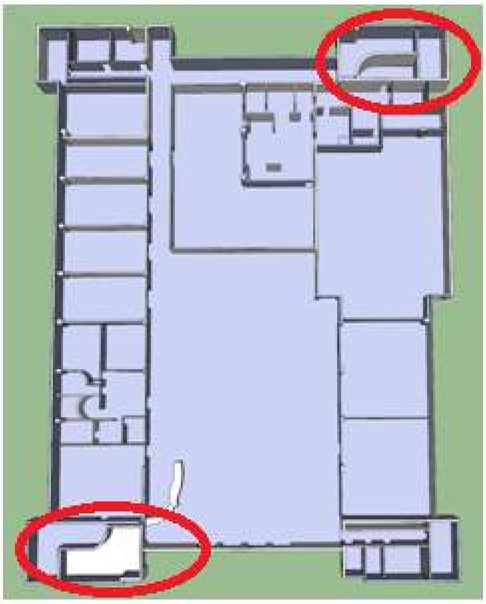


Figure 6.8 – Illustration of the building first floor.

For the simulation, the full environment is mapped in order to specify walkable regions for the agents. This process is performed by *CrowdSim* configuration module (see Figure 6.7-c). The green areas represent the *starting* areas, regions where the agents can be created, while the external areas of the building (*goal* areas) are presented in red and are located near to emergency exits. Connecting *start* and *goal* areas we can observe the *walkable* areas (corridors and stairs) illustrated in blue.

To set up the simulation scenario we take into account the average number of people at each floor of the building, during a normal day of work. Table 6.1 summarizes the numbers of simulated people. It is important to mention that this population distribution was similar when performing the real evacuation exercise.

Floor	1	2	3	4	5	6	7	8	**Total**
Agents	100	190	200	130	85	55	50	20	**830**

Table 6.1 – Population simulated in each floor of the college building.

The high concentration of people in the first four floors is mainly because in this area are located most part of the classrooms and practical laboratories for classes. In the other floors are located research labs, professors and business offices. In the performed simulation all the agents are configured to leave the building using emergency exists except the agents from first floor. The same orientation was considered when performed the real evacuation exercise.

Table 6.2 summarizes the obtained information from real and simulated evacuation process. The evacuation times are presented in seconds. In order to have parameters of analyze for each of the processes, two points of observation are defined:

1. *Safe Areas*: We consider as a safe area the building region located after the emergency exit on each floor. More specifically, these areas represent the stairs used during the evacuation.
2. *Outside Areas*: The goal areas outside the building.

Place	Real Process		Simulation	
	Time to first person achieve the safe area	Time to first person leave the building	Time to first agent achieve the safe area	Time to first agent leave the building
Classroom 205	30		32	56
Classroom 214	35	100	34	64
Classroom 301		180	52	68
Lab 309	40	163	38	76
Lab 310	25	120	16	64
Classroom 312		154	57	116
Classroom 412		312	54	132
Classroom 415		300	41	118
Professors Room (5th floor)		274	55	159

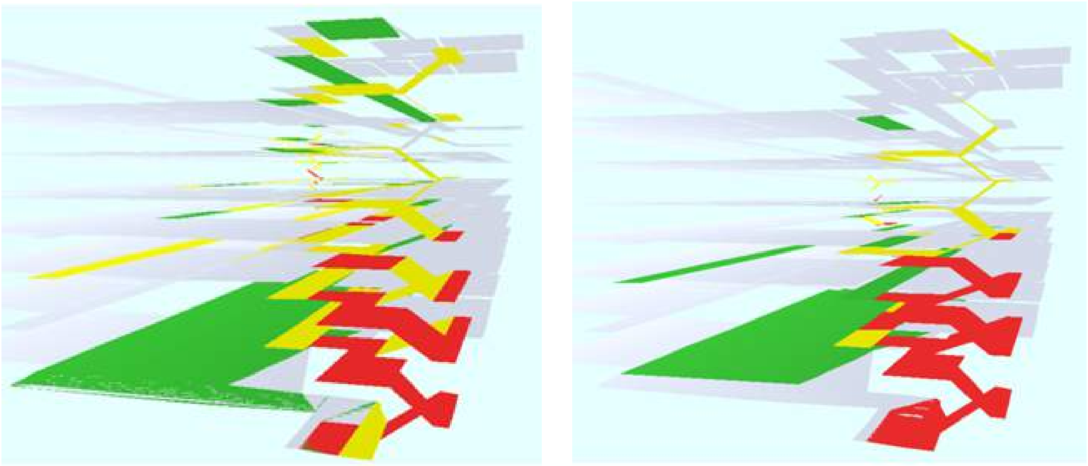
Table 6.2 – Summarized data from college building evacuation: real and simulated process. Some cells are empty because we could not obtain the data in real life.

In the real egress exercise we had the collaboration of some volunteers who timed their walk time until they reach the safe and goal areas. Unfortunately, in some rooms, we could not have information. A quick analyzes of the extracted data from real and simulation scenarios allows us to observe that the differences are small and coherent. We believe that the difference between the simulation and the real exercise time is because all the simulation agents were created and started to move in the exact same time, in a different way from real life, where people have different response time to events. Another point to be considered is regarding to the agents velocity. According to literature [24], we specify the velocity of the agents in $0.8m/s$ adding a positive and negative variation of 20%.

Analyzing just the classroom 309 we can observe a divergence between the simulation time (76 seconds) and real process time (163 seconds). After contacting people from classroom 309 we were informed that they decide to organize their bags and scholar material before leaving. We consider that is a reaction that should not happen in a real emergency event and it contributed for the large difference between the reported times.

After the simulation finished, we observed that the time taken for all the agents leave the building was 250 seconds (4 minutes and 10 seconds). On the other hand, the last person to leave the building in the real evacuation exercise left at time of 7 min and 34 seconds (454 seconds).

The analyzes of the simulation results provided by *CrowdSim* allows us to compute the density of the place during the simulated evacuation process. The density analysis makes possible to identify attention points in the environment including bottlenecks. In Figure 6.9 we present a density map where we illustrate the environment density, specifically on the stairs located on the frontal emergency exit in two distinct moments of simulation (after 40 (a) and 80 (b) seconds of simulation). The regions in red mean attention areas (more than 2 people per sqm) while the yellow and green areas mean regions with medium (2 people per sqm) and low (1 person per sqm) concentration of people.



(a) (b)

Figure 6.9 – Density maps of college building in two distinct moments of simulation (after 40 (a) and 80 (b) seconds of simulation.

As expected, the greater concentration points are located in the first and the fourth floors. The high concentration in these regions starts after 40 seconds of simulation when agents from highest floors achieve half of distance to reach the goal areas outside the building.

6.1.4 School

In this case study we applied *CrowdSim* in a school that receive kindergartens, elementary, middle and high school students. The project was performed at Pastor Dohms School[5], in Porto Alegre - Brazil. The first step was to reproduce the school in a 3D environment as requested input. Subsequently, we defined the environment constraints as well as the desired behaviors according to the steps enumerated as follows:

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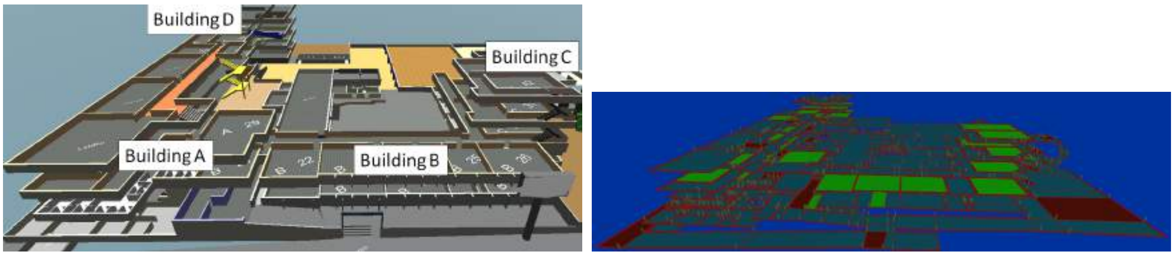
[5] `http://dohms.org.br/`

1. we specified the regions where motion is allowed (e.g corridors and stairs) in the 3D environment. Moreover we defined the regions where the agents should be created (i.e. class rooms) and the regions to be considered as goals (i.e. exit doors). Such information is taken into account by *CrowdSim* when running path planing in order to compute agents routes. Figure 6.10 illustrates the school 3D model (a) and the environment mapped into *CrowdSim* in (b).

2. The population data was defined according to school staff specifications. We were able to define the number of agents to be simulated as well as their goals during simulation. In order to specify such information, we have considered the values according to the real occupation of the school for each classroom, at each building (as illustrated in Figure 6.10(a). Also, we observed the best school exit to be considered in an egress process according the school structure. The school has two exits that are considered by the students when leaving the building in normal days. In addition, we observed the existence of extra doors (not used by the students) that are able to be considered by additional routes when thinking about egress process. The school structure allow us to validate different routes for possible egress situation that are further described.



(a) (b)

Figure 6.10 – The school environment modeled in 3D (a) and the environment specification in *CrowdSim*(b).

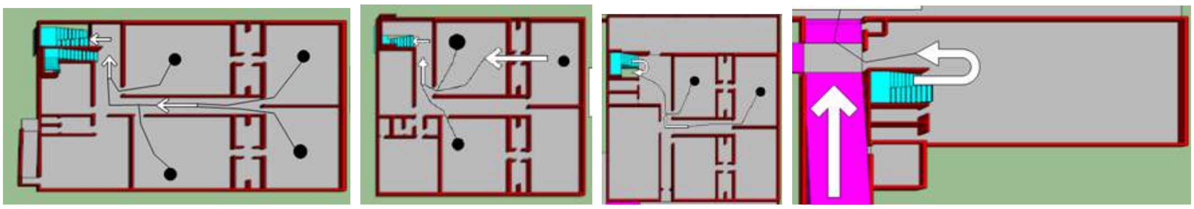
After the environment and population constraints specifications, we performed simulations according to four different scenarios. Such scenarios were defined considering the school population in the morning (1067 students) and afternoon (729 people) as well as available exists (Figure 6.11 illustrates the available exits considered in the experiments).

Figure 6.11 – Available exits from the school.

The four simulated scenarios are:

1. morning population with only the main exits available;
2. afternoon population with only the main exits available;
3. morning population with all exits available;
4. afternoon population with all exits available.

In order to test the four scenarios, it was necessary to define routes able to guide the agents until the nearest exit, according to the classrooms' locations. The routes represent, at this point, an evacuation plan to be performed. In this work, four evacuation plans have been developed according to the specification of each evacuation scenario. Figure 6.12 illustrates the routes to be followed by the agents that should leave the Building D of the school. The lines indicate the path to be followed while the white arrows represent the direction of the motion. As previously illustrated in Figure 6.10(a) the school is composed by four buildings of classrooms.



(a) 4th Floor (b) 3rd Floor (c) 2nd Floor (d) 1th Floor

Figure 6.12 – Routes representing the evacuation plan of Building D.

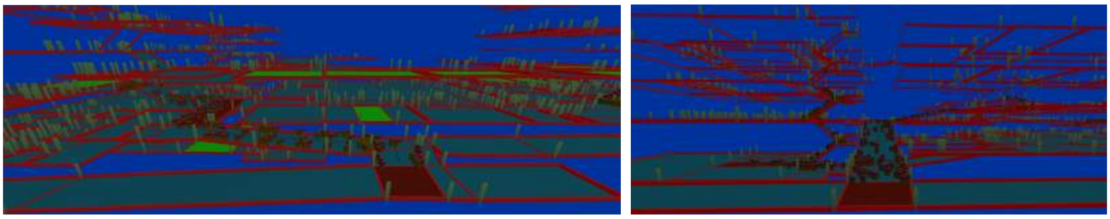
Besides setting the evacuation plans (environment and people data, behaviors and routes) it is important to emphasize some points to be observed during the simulation of all scenarios:

- The people distribution per classroom was computed according to data provided from school staff.
- We consider a reaction time for all scenarios. This time represents the response time of each agent until it starts to move after received an orientation to egress. We considered the response time as $5s$ for all the experiments.
- The agents are not created in the exact same time. In the experiments, we created groups from 1 to 10 agents (in each classroom) observing an interval of 10 seconds. This procedure was adopted to avoid that all agents start to move at the same time.
- All agents aim to move at speed of 0.8 m/s.

Table 6.3 summarizes the obtained results from performed simulations. Also, Figure 6.13 shows two frames from distinct simulations, which aim to illustrate the two main exits from school taken into account during the simulation of egress.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of agents	1067	729	1067	729
Total Evacuation Time	217s	207s	214s	172s
AVG Evacuation Time	98s	88s	88s	78s
Smallest Evacuation Time	31s	33s	16s	16s
Greater walked distance	132m	112m	130m	103m
AVG walked Distance	74m	68m	67m	59m
Smaller walked distance	30m	23m	21m	20m
Higher speed	1.5 m/s	1.59 m/s	1.5 m/s	1.5 m/s
AVG speed	0.81 m/s	0.82 m/s	0.82 m/s	0.81 m/s
Smallest speed	0.29 m/s	0.10 m/s	0.45 m/s	0.13 m/s
Higher observed density	6 people /sqm (at second 61)	4 people /s qm (at second 50)	5 people / sqm (at second 61)	4 people / sqm (second 60)
AVG of higher densities	2.2 people/sqm	2.2 people /sqm	1.79 people/sqm	1.49 people / sqm
Std deviation of higher densities	1.87	1.88	1.72	1.34

Table 6.3 – Summary of performed simulations.



(a) Main Exit 1 in CrowdSim (b) Main Exit 1 in Game4Safety

Figure 6.13 – Two simulation frames illustrating the position of the two main exits of the school.

The analyzes of crowd simulation results have allowed us to observe different points of attention during the egress process. One important point is concerned to the variation of density in the buildings of school during the evacuation. The statistical data has shown the time of simulation when the higher density was detected. The estimation of the time for higher density allowed us to analyze the simulation and environment in order to identify the place of high density as an attention region. In the four simulated scenarios, the higher density have occurred in the stair of buildings C (scenarios 1 and 3) and D (scenarios 2 and 4). Figure 6.14 presents two frames of simulation when the highest density was detected on Building C (left) and Building D (right).

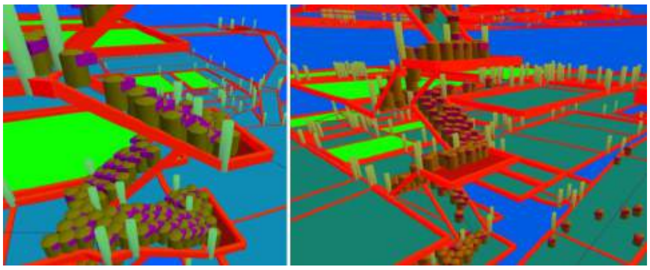


Figure 6.14 – Highest density detected by simulations in Building C (left) and Building D (right).

At this point, all simulated agents follow the same behavior during the egress. However, one of the concerns from the school manager was related to one special building of the school: Building D, where the kinder garden classrooms are located. We know that small kids usually present different behavior of teenagers or adults, specially when they are part of an evacuation process. In order to deal with this situation, we implemented a new rule in *CrowdSim*: we propose to implement an individual attribute in the agents called “goals persistence", which is related to a factor that represents how much time the agents seek goals during the simulation. This factor makes the agents ignore the goal seeking behavior and remain wandering during some specific time. We did not found any specific literature about children behavior in evacuation scenarios, in order to validate our approach. In this way, we empirically applied the factor in order to represent the following case: The children of Building D should perform goal seeking behavior during 4 seconds and keep wandering during other 8 seconds. Experimental simulations have shown that the Building D is evacuated in 260 seconds, without goals persistence factor, while the time increases to 325 seconds when such factor is applied.

After these simulations, we could observe that *CrowdSim* is capable to simulate different environments and population characteristics. Finally, we observed that the software is easily adaptable, since we could simulate a population of kinder garden children with just minor modifications in the model. However, we noticed that the numerical output of the software, besides its utility for evaluation of the school safety, is not good enough for training the children and teenagers of the school. In order to improve this feature, we developed a game like interactive tool that allows students to embody the simulation results in a more attractive and engaging way. The next section details this improvement.

The Game

One reason for the growing interest in games is the engagement that they arouse in the players. In an opposite trend than entertainment, games can also be used to direct this engagement for improving users' learning and training. In that sense, serious games can be thought as an efficient tool to educate and train people aiming to develop, for example, an intrinsic thinking of safety. One point addressed in this project focuses on the importance to engage kids in the training of evacuation processes. Usually, buildings may have hundreds or thousands of occupants and, sometimes, many of them are not aware of the architect layout in order to know the safest exit from their location [29].

When we are working with crowd simulation in safety applications, it is very common to analyze the produced data according some statistical criteria. Once this project was performed at a scholar environment, however, the customer is not only the school managers team. We are very interested in developing a culture of safety on the students and their families. We believe that games can be a powerful tool in order to achieve this goal. Indeed, the use of games to illustrate simulation data have been previously used in approaches from different authors. The *Emergency Evacuation Simulator*[6] used a game engine to develop a tool for training for emergency. In the same way, Shatz *et al.* [69] proposes a Building Information Modeling based serious game able to produce fire safety evacuation simulations.

Aiming to engage the students and make they able to think about safety, we created a game-

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[6] `http://www.program-ace.com/portfolio/case-studies/emergency-evacuation-simulator`

based interactive visualization tool. The student can learn and really understand as well as virtually be part of a possible egress process from their own school. This tool was called *Game4Safety* and was developed according to the following requirements:

1. *To recreate the realistic training environment (precise 3D model of the school):* we reproduce the interior of the school according to its physical structure. At first, we do not consider furniture due to the time consuming work necessary to reproduce the details on each classroom. It is important to mention that the approach presented here is able to consider furniture as obstacles if their 3D models was available;

2. *the student should be able to explore the school space in its normal state:* as in First-person-shooter (FPS) game, the player is able to navigate in the environment as one of the characters present on it. Also, the player is also able to navigate as in a Real-time strategy (RTS) game;

3. *it must be possible to the users to observe the way out and the shortest routes to the exits from different locations in the environment:* the player must be able to choose a specific classroom of the school. With this feature, the camera is positioned on such point of the environment and the user is able to observe the best route to leave the school from that point. Also, the player can adopt a FPS camera view and move around the environment according the presented route;

4. *to allow time monitoring:* we allow the player to select one specific virtual human to monitor his/her behavior when evacuating; and

5. *to emulate different population scenarios:* when running the game, the player is able to choose among different scenarios to explore. Such set of scenarios represent 4 different simulations performed according to populations on the school during different periods of the day (morning and afternoon) and also the variation of available exits. We considered the normal exits used by students in normal days and also presented scenarios taking into account emergency exits simulating a possible emergency egress process.

In order to meet such features and requirements, a prototype based on Unity 3D game engine[7] was developed. Figure 6.15 illustrates a comparative of a simple simulation visualization in *CrowdSim* and the same point visualized in *Game4Safety*.

By starting *Game4Safety*, the player is able to select one of four available scenarios to be loaded. When the scenario is loaded, the user can interact with the environment and play a simulation. These options are available to the player on the developed interface:

- To choose the best camera to explore the environment (RTS or FPS). Controls are available on keyboard;

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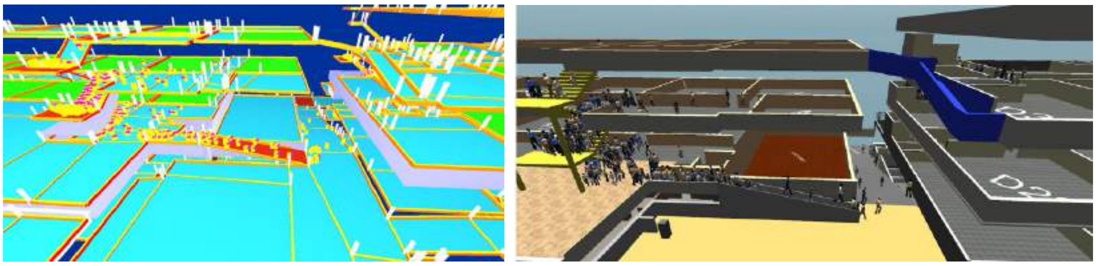
[7] `https://unity3d.com`

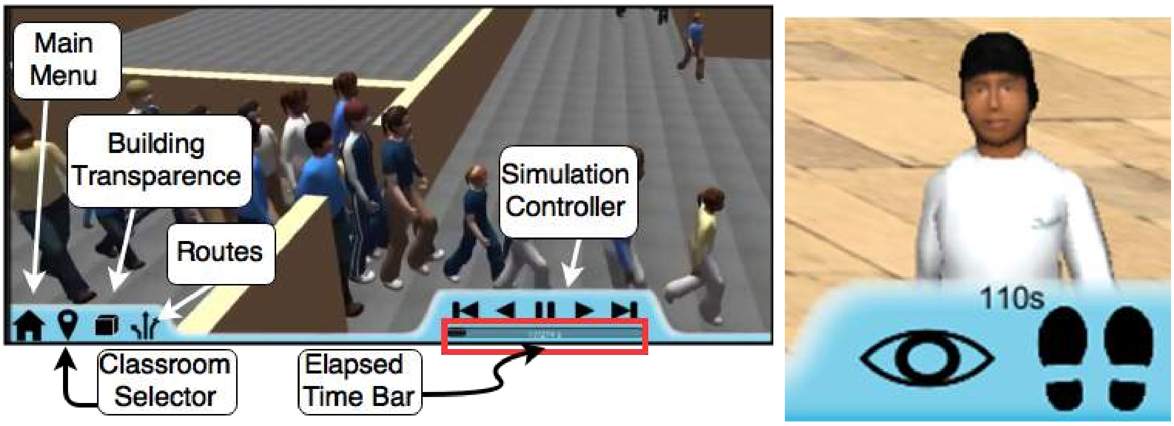


(a) Main Exit 1 (b) Main Exit 1

Figure 6.15 – Illustration of the simulation environment in CrowdSim (a), and the same point of view in the game engine (b).

- to see the available routes for the virtual humans. The user can also select one specific virtual human by click on it. When a virtual human is selected, specific information about he/she is displayed (e.g. total time to the virtual human leave the school and the followed route) - See Figure 6.16(b). The player can follow the virtual human during the motion or also assume the character point of view;
- To apply transparency in the building in order to better visualize the 3D characters as well as the routes;
- To select a specific classroom and be transported to such location in the virtual environment;
- To increase the speed of visualization, back to initial point and also go to end point of simulation; and
- To visualize the elapsed time of simulation, in seconds.

An illustration of the interface controllers is available in Figure 6.16(a).



(a) (b)

Figure 6.16 – Application Controller Interface (a) where it is possible to detail an specific agent (b)

In order to verify the efficiency of Game4Safety, a supervised play test section was performed. A group composed by 10 students aged from 12 to 15 years and also 2 members of school staff have been part of the validation process of the game. During the play test section the testers were observed by the development team of Game4Safety.

Figure 6.17 – Students playing Game4Safety.

After exploring *Game4Safety*, some testimonials from the group of testers have been collected. The overall impression of the group tester was positive and, according to them, very helpful in order to learn how a possible evacuation process can be performed in the school. Some of them are presented next:

- *This is an important tool in order to develop a useful evacuation plan. It is a different approach to develop safety thinking in the students*. School's Principal.
- *The game is very cool and we can learn when playing. I went to my classroom and now I know how to leave the school when in emergency. It is very important to our safety.* Student, 13 years.
- *This game can help me and my colleagues to understand and think what is the safest way to leave the school in a possible emergency situation. The game also can help other schools*. Student, 14 years.

The analyzes of testimonials indicates the applicability of *Game4Safety*. The game is currently used in the school in order to train the students, and also their families about the importance of evacuation scenarios and a culture of safety.

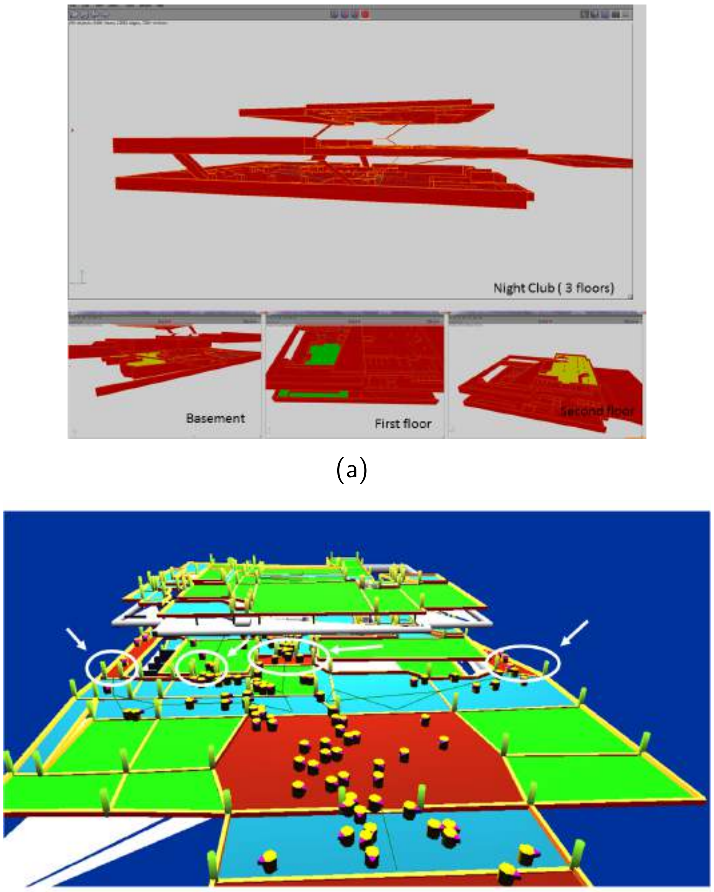
Final Considerations about this Project :

In this project it was detailed the application of *CrowdSim* in order to simulate different scenarios in a School. Obtained data from simulations are useful to school managers in order to specify the best way to evacuate the school in a possible emergency situation. In addition, we develop *Game4Safety* in order to provide an interactive way for the students to analyze obtained data of performed simulations.

The use of *Game4Safety* can improve the students engagement in the training process concerning building exploration and evacuation. Obtained results as well as the the students feedback to the project have shown its applicability. In addition the game was subject of TV media on the news of our state (see Appendix B.2). Also, the results from this project are already published [15].

6.1.5 Night Club

In this section we detail the application of *CrowdSim* in a night club, in Porto Alegre, Brazil. Our goal was to study how people perform an evacuation process in real life and thus obtain data to allow quantitative comparisons. The experiment was a shared experience developed in partnership with the night club owners and a safety company. On the day the experiment was conducted, the audience agreed to leave the club exactly at 2AM. Some days before the egress exercise in the club, *CrowdSim* was applied in order to provide different evacuation plans that could be used to estimate occupant behavior. The first step of the process was to reproduce the club environment in 3D. The environment has a total area of 1010 sqm and has 4 floors (see Figure 6.18(b) to see the door locations). A 3D representation is illustrated in Figure 6.18(a).



(a)

(b)

Figure 6.18 – Illustration of the 3D model of the night club and the location of its exit doors in *CrowdSim*.

The 3D environment was necessary in order to allow the definition of the possible evacuation plans. This is because we specify in the 3D model, all the regions where agents need to be inserted and removed from the simulation and also we specify the regions where the motion is allowed. The specification of the environment, defined in the configuration module of *CrowdSim* according to the 3D model of the club, makes possible to build an environmental graph. Such graph is illustrated in Figure 6.19 and it is composed by three different types of nodes which are represented by different colors:

1. Orange nodes represent decision areas. In such areas of the club, where agents can be created, they need to chose different routes from that point. This nodes represent the bifurcations in the graph;
2. Green nodes are representing the stairs responsible for connecting the different floors of the club. No agents are created in such regions that are considered just motion areas; and
3. White nodes are regions where agents can be created in the simulation and also, walkable areas. The only exception is the node called *Street* that is responsible for removing the agents in the simulation (exit context).

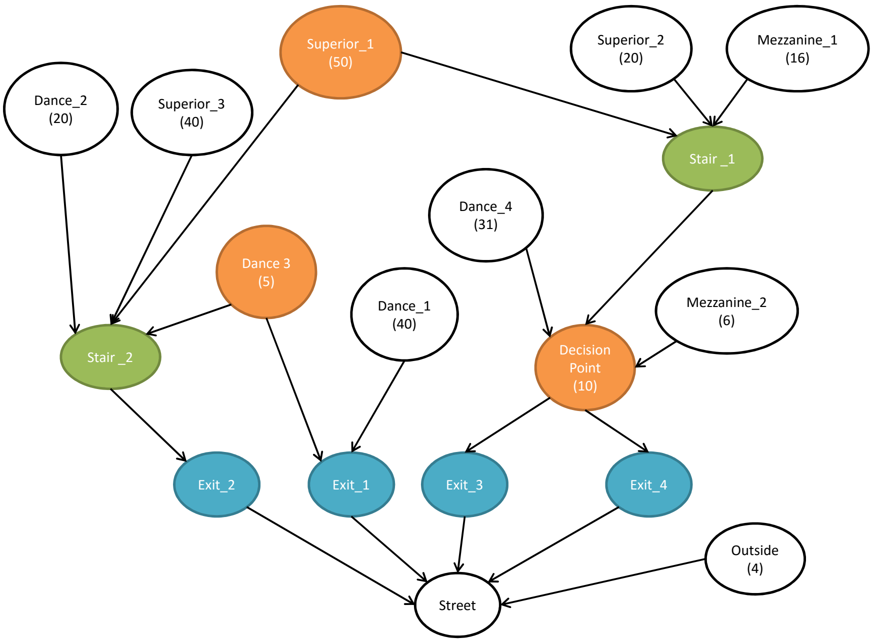


Figure 6.19 – Night club's graph specifying the environment structure to be considered in the generation of possible evacuation routes. All the nodes means walkable regions while the edges represent the doors connecting the rooms of the place. In addition, orange nodes means decision areas (where the agents can chose different paths) while green nodes represent the stairs connecting the different floors of the night club.

Indeed, this graph is a simplification of automated graph that is generated by CrowdSim (please see Fig. 6.31(a)). The graph also presents the population which is created in each node.

The safety company had generated different evacuation plans using *CrowdSim*. In Table 6.4 are the results obtained from three evacuation plans designed and tested in *CrowdSim* by the safety engineers (see Figure 6.21 containing two frames from one of the performed simulations). The difference among the 3 evacuated plans (highlighted in Figures 6.20) is related to the number of people in the 3 bifurcations. Based on such distributions, the people who used the 4 different exit doors changed, as shown in the last four lines in Table 6.4. Indeed, it is easy to show that doors 3 and 4 received more people than the other two. This happened because doors 3 and 4 are larger and could accommodate more people.

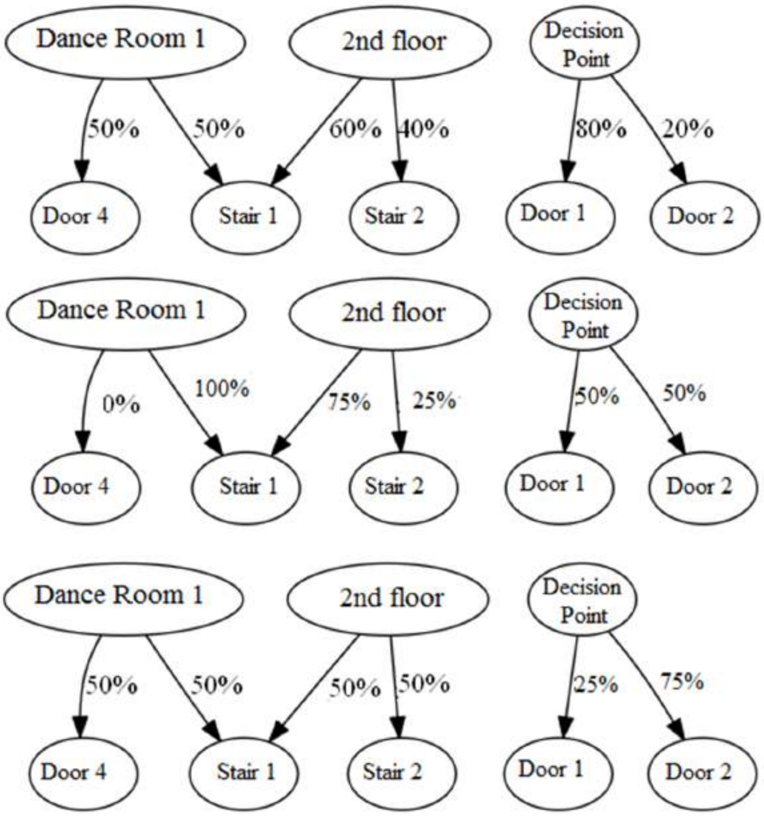


Figure 6.20 – Three examples of evacuation plan tested by our model: Simulations ids: 1, 2 and 3, as related in Table 6.4.

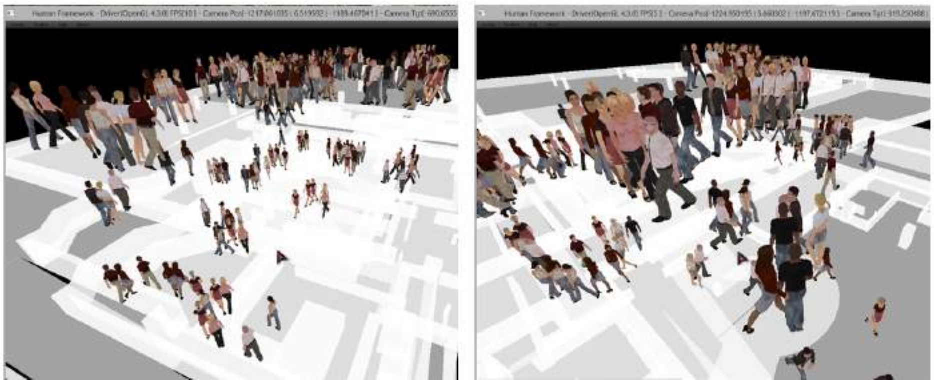


Figure 6.21 – Images illustrating the simulation.

After performing several simulations, it was possible to identify a set of plausible evacuations plans to be performed in the real life exercise. In Table 6.4 we present the results computed of three evacuation plans that have been designed and tested in *CrowdSim* by the safety engineers.

	Simulation 1	Simulation 2	Simulation 3
gt_i (sec)	142	142	146
at_i (sec)	61	62	64
$ad_i\ (people/m^2)$	0.1123	0.1138	0.1162
$av_i\ m/s$	0.80	0.80	0.80
Place of biggest density	2nd floor stairs	2nd floor stairs	2nd floor stairs
Time when biggest density was observed	Second 40	Second 39	Second 50
Biggest speed (m/s)	1.3	1.2	1.3
Smallest speed (m/s)	0.01	0.01	0.005
Biggest Local Density	5.4	5.4	5.0
Computed ep_i	1.35811	1.36549	1.3953
Number of people in Door1	54	18	21
Number of people in Door2	12	41	50
Number of people in Door3	80	126	75
Number of people in Door4	100	61	100

Table 6.4 – Quantitative data comparing simulated scenarios containing 240 people.

Considering $a_{ref} = (35.15, 0.73)$ (agent reference values specified in Sec. 4.3) and applying Equation 4.6, following values for ep were obtained: $ep_1 = 1.35811$, $ep_2 = 1.36549$ and $ep_3 = 1.3953$, respectively for the 3 simulated plans. Plan of Simulation 1 has been selected and used in a real life scenario. Please, note that even if one wants to consider the individual metrics (gt, at, ad and av) the best plan is still plan of Simulation 1. Figure 6.22 specifies the percentage values to indicate the specifications of the chosen plan: how many agents should follow each route available on decision areas of the club (see orange nodes in Fig. 6.19).

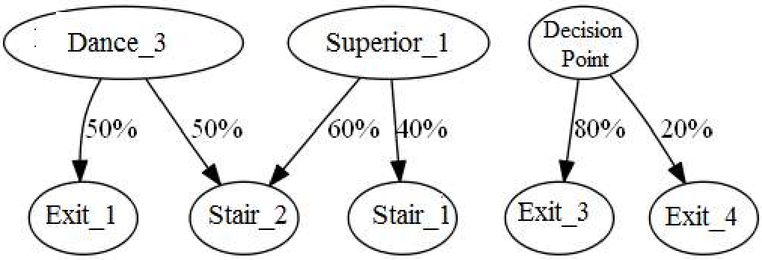


Figure 6.22 – Sub-graph illustrating the percentage of agents who should follow by each path of the bifurcations in the graph. This sub-graph represent the reference plan used in real life.

Once the plan was selected, the safety company began to train individuals who work in the Night Club. The real evacuation was performed with 240 people who agreed to participate in the experience. During the real egress exercise, we were able to collect different data in order to evaluate results of this experience. Occupant data was obtained from security camera videos. The number of people in different parts of the club was obtained from infra-red technology. This information was very important in order to evaluate this work. Table 6.5 summarizes the comparison between real and virtual evacuation scenarios.

	Simulation	Real World Data
Total time for evacuation (seconds)	119	175
Highest Density (people/m^2)	5.4	4.5
Place of highest density	Stairs (2nd floor)	Stairs (2nd floor)
Time when highest density was observed	Second 40	Second 50
Highest speed (m/s)	1.3	1.5
Smallest speed (m/s)	0.1	0.2

Table 6.5 – Quantitative data comparing real and simulated worlds considering exactly the same evacuation plan.

Figure 6.23 provides an image captured during the evacuation that shows the people in stairs (2nd floor) at 40 seconds after the simulation started, and another image at the same place and time in the virtual simulation.

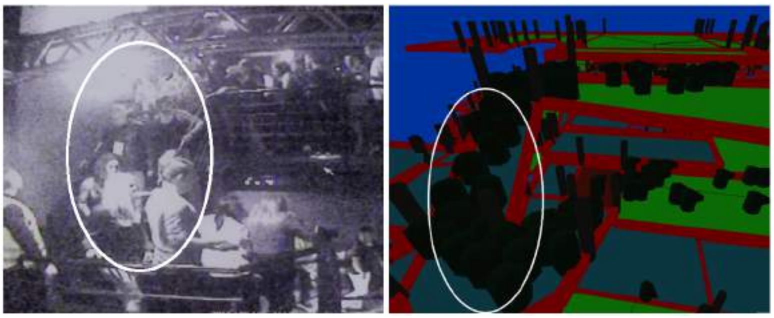


Figure 6.23 – Images illustrating the stairs in the 2nd floor 40 seconds after the beginning of the simulation in real and virtual environment.

When analyzing Table 6.5 there are clear differences in evacuation time. It can be explained by the fact that real people do not voluntarily behave the same as they would in a true emergency. That is, real people, not in panic, respect the space of others, and therefore do not achieve the higher densities apparent in the simulation data.

6.2 Simulation of heterogeneous agents under alcohol influence

The emergent characteristics of crowds can represent several independent behaviors; in this way, recent scientific studies have considered crowds as an *entity able to think* [50]. Such thinking came to endorse the idea that crowds are composed by independent individuals, each one with the own needs and ways of thinking.

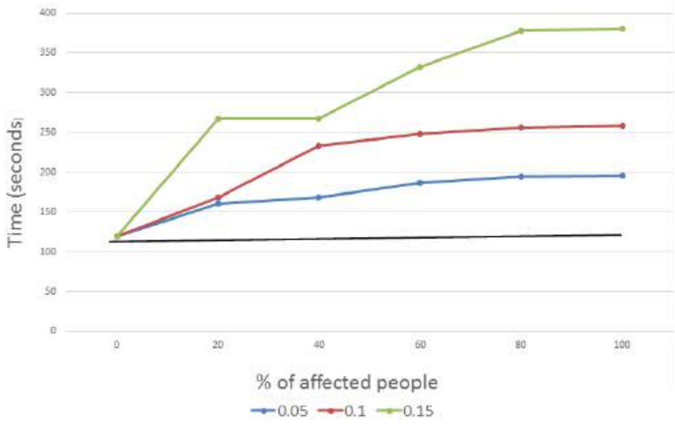
The individuality can be represented by many factors as the gender, age of each individual or her/his physical state. An important aspect in crowd behaviors is how such factors can influence on crowd evolution/simulation. The main question of this experiment is:

Can the crowd be affected when its members or part of them are not in their perfect physical or mental state?

Situations where individuals physical state varies can be observed in mostly all contexts of real life. The important question in the context of crowd simulation is to know when such differences are relevant to be considered in a simulation, since the simulation of heterogeneous crowds (if compared to homogeneous crowds) obviously includes complexities to be dealt with. In this section, we investigate how some differences in individual behaviors (e.g. caused by alcohol) can influence the crowd behavior. Inspired on available literature (World Health Organization[8]) we simulate the behavior of agents affected by alcohol in a nightclub.

We used the night-club simulation (see Sec. 6.1.5) in order to have simulations that were compared with real life, and presented data that we considered comparable. The difference is that we reproduce the simulations considering heterogeneous agents in order to represent people under alcohol influence. For this experiment, we worked with a population of 240 people (the same population on the real life egress exercise).

We considered three different scenarios having varied number from total population been affected by BAC level (i.e. simulating percentage of people who drank and how much), please refer to Section 4.2 for details. The tested BAC levels were: 0.05, 0.1 and 0.15 in percentages of population from 0 to 100%. We did not test higher levels of BAC because impacted agents could not move, since according to Table 4.1 people in such levels have several motor impairments and can even lose consciousness. As can be seen in Figure 6.24 the simulation time is highly affected by increasing BAC level (black line has been used as reference for time obtained with non affected population). Computing the average time obtained with BAC$= 0.05$ for percentage from 20 to 100 of total population, we have a value 26% greater than when agents were homogeneous. For BAC$= 0.1$ and 0.15 the obtained values are respectively 62% and 127% greater than for homogeneous crowds.



BAC level	gp	Frames to goal	Frames wandering
0,00	1,00	10	0
0,05	0,69	7	3
0,10	0,48	5	5
0,15	0,33	3	7
0,29	0,12	1	9
0,39	0,05	1	9

Figure 6.24 – Simulated data presenting the variation of evacuation time when BAC increases.

As can be seen in Figure 6.24 for BAC levels 0.05 and 0.1 simulation time is not highly impacted

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[8] http://www.who.int/

when 40% or more of the agents are affected by alcohol. This was not the expected behavior, but after many tests, we concluded that when almost half of the population is affected (uniformly distributed in the space), they disturb all agents (even the ones who are already affected), and consequently everybody takes more time to evacuate the environment. In addition, in Figure 6.24 we can see the computed values gp_k, nf_k (frames keeping goal) and $f - nf_k$ (frames wandering) for agent k in certain BAC level. In these evaluations we considered $f = 10$ (as explained in Section 4.2). BAC levels of 0.29 and 0.39 have been simulated however a big part of agents could not leave the environment, so we could not measure the final time of simulation.

We were not able to compare virtual heterogeneous crowds with real life, since we do not have real data about BAC levels in real people. A contribution of this report in this aspect is the modeling of heterogeneous crowds based on alcohol literature. The results obtained by this project are already published in [14].

6.3 Using EP to Evaluate Evacuation Plans in the Night Club

Previously, in Section 6.1.5, we detailed the application of a *CrowdSim* in a project performed in a Night Club. The study of such project allowed us to investigate if the applied plan at that time, in order to evacuate that environment, was the ideal plan.

In this section we detail discussions about the proposed metric EP (presented in Section 4.3) performed with main goal to try identify the best evacuation plan according to the night club constraints. Figure 6.25 illustrates the entire performed pipeline that we define in order to connect all performed process:

- *Training Process*: This process is responsible for, since a standard evacuation scenario is defined on *CrowdSim* to compute statistical data about it. When a population is defined we are able to generate different ways to such people leave the building (according to definition from Section 4.3) in order to evaluate them aiming to identify the best. To such investigation we consider a database composed by data from diverse simulation.
- *Simulation Process*: We simulate the best selected and store statistical data.
- *Real Evacuation Exercise*: When possible, we support real-life egress exercises. Usually, this kind of experiment is managed by a safety team. We observe the process in order to collect and store data.
- *Evaluation*: Different analyzes are performed in order to compare different plans, based on data from different sources: since simulated data as well as real data.

For this experiment we considered the case study performed in the night club, previously described in Section 6.1.5. As the input, we have considered the environmental graph which represents the connections that can be found in the night club in order to generate possible routes (see previous

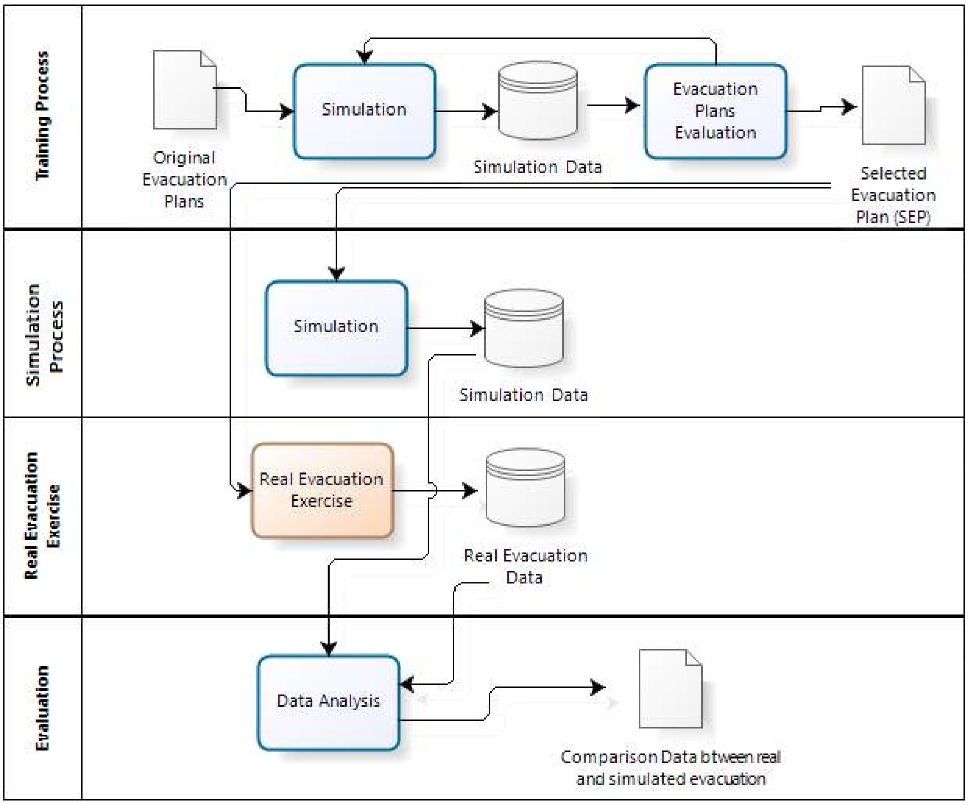


Figure 6.25 – Pipeline of the entire process for ep evaluation.

Figure 6.19). We performed the plans' generation process considering the previous illustrated graph together with a 10% granularity for a population of 240 people. A total of 1331 possible evacuation plans were generated. Further, we updated the population distributed in the night club in order to compute others scenario aiming to represent a full house scenario (1010 agents), when considering $1 person/m^2$. Thus, the plans generation process was repeated in order to compute the 1331 plans possible to be executed, but now in a full house scenario.

After the two experiments, a total of 2662 simulations were performed by *CrowdSim* in order to investigate the best way to evacuate the club for different populations. Next we detail the results of our studies in order to attend the steps from our pipeline (Fig. 6.25). It is important to mention that we computed ep values for all plans from both scenarios and ranked them, including also in the rank the evacuation plan used in real experiment with 240 people, denoted in this section as ep_{ref}.

6.3.1 Evaluating the Night Club containing 240 agents

The goal of this experiment is to study the best way to evacuate the night club when comparing with the scenario performed in the real life experience. The first step of the experiment was to simulate all the generated plans for this scenario in order to compute statistical information. After the simulation of 1331 evacuation plans we obtained follow data for each plan i:

- Average density (ad_i);
- average speed performed by the agents (as_i);

- average of agents' life time (at_i); and
- total time of simulation (tt_i).

Such information allowed us to compute the ep values for the 1331 plans. Table 6.6 summarizes the computed data of the best 20 plans for this scenario, w.r.t. ep values. In addition to simulation results we included the percentages of people used in the three bifurcations, as illustrated in Figure 6.22. We called pag, sup and $v4$ the percentages for each bifurcation, defined in the left edges. The simulations were computed using the same fixed seed (empirically used equal to 8), in order to calculate the same scenario variations for the plans.

Plan_Id	Computed_ep	avgDensity	avgSpeed	avglifeTime	totalTime	pag	sup	$v4$
	(ep)	(ad_i)	(as_i)	(at_i)	(tt_i)			
1209	1.3081	0.1091	0.8048	1776.15	3732	10	100	100
1327	1.3081	0.1091	0.8048	1776.15	3732	0	100	100
385	1.3083	0.109553	0.804878	1781.83	3708	20	90	100
706	1.3087	0.109517	0.804878	1781.42	3716	20	100	100
1132	1.3089	0.109647	0.804878	1783.83	3708	20	90	90
322	1.30891	0.109647	0.804878	1783.84	3708	80	90	100
1203	1.30891	0.109647	0.804878	1783.84	3708	100	90	100
1289	1.30891	0.109647	0.804878	1783.84	3708	90	90	100
48	1.30912	0.109588	0.804878	1782.83	3716	90	100	100
386	1.30912	0.109588	0.804878	1782.83	3716	80	100	100
616	1.30912	0.109588	0.804878	1782.83	3716	100	100	100
1094	1.30945	0.109553	0.804878	1781.94	3725	30	90	100
592	1.30952	0.10957	0.804878	1782.41	3724	60	100	90
871	1.30952	0.10957	0.804878	1782.41	3724	40	100	90
1237	1.30952	0.10957	0.804878	1782.41	3724	50	100	90
520	1.31003	0.1097	0.804878	1783.82	3725	30	80	100
176	1.31022	0.109919	0.804878	1788.15	3708	80	80	100
272	1.31022	0.109919	0.804878	1788.15	3708	100	80	100
1196	1.31022	0.109919	0.804878	1788.15	3708	90	80	100

Table 6.6 – Obtained data from the best 20 evacuation plans considering 240 agents, w.r.t to ep values.

Figure 6.26 illustrates the difference from the ep_{ref} (real life) to all the computed plans. It is important to highlight that in X axes (Evacuation plans) the order is the same for all the graphics in this section, i.e. the plans are ordered based on their ep values. We also illustrate the difference from specific attributes from the plan performed in real-life and the computed plans. This differences are illustrated in Figure 6.27 and consider aspects of: average life time 6.27(a) and total time 6.27(b) of evacuation plans w.r.t ep_{ref} (again evacuation plans - X axis - are in the same order than in Figure. 6.26).

As could be seen in the the graphics, other plans were better evaluated if we consider ep metric, but also if we consider the individual metrics. Indeed, ep_{ref} is ranked in 663^{th} position. Of course it

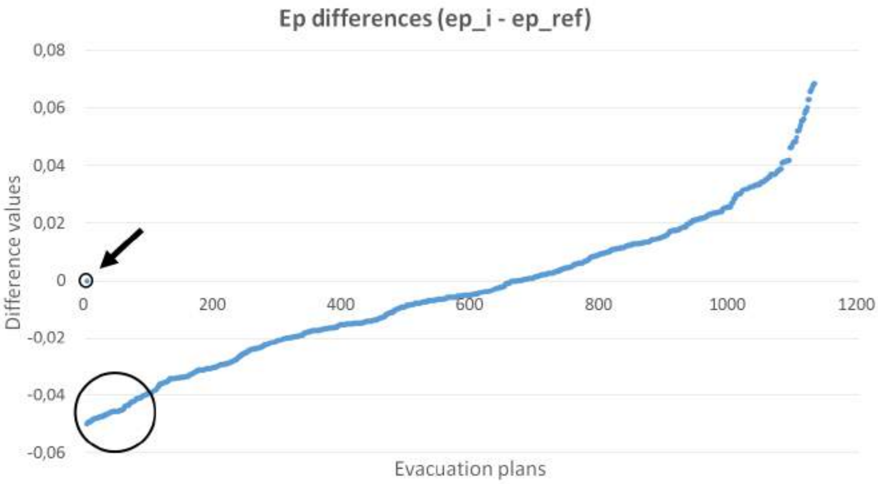
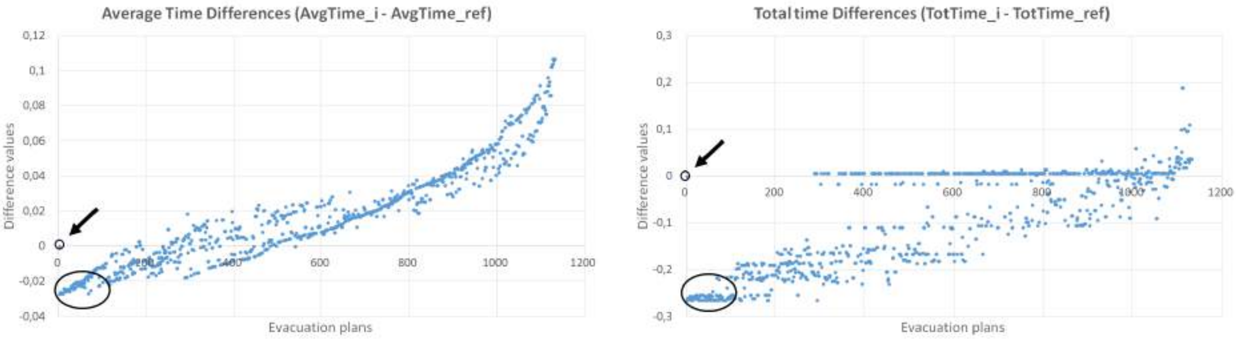


Figure 6.26 – Difference between ep value from real life experience (highlighted with an arrow) and all 1331 evaluated plans. The black circle highlights the best 20 evaluated plans w.r.t. computed ep values.



(a) Avg. time difference

(b) Total time difference

Figure 6.27 – Attributes of all computed plans. (a) and (b) are related to difference between ep_{ref} and all plans.

depends on granularity, because depending on the discretization many evacuation plans can be very similar. For instance, considering granularity of 25%, we generated 125 plans and ep_{ref} was ranked in 23^th position. Even if the real life experiment was guided using the 663^{th} ranked evacuation plan, it is important to consider that the difference between ep_{ref} and all ep_i better than it are maximum 0.049 over the total difference (from the best to the last ranked plans)$=0.118$. In order to present more detail about the evaluated and best plans, we discuss the plots of Figure 6.28, considering ad_i, at_i and gt_i to evaluate the plans. Desired velocities have been fixed for all simulations, and since night club were simulated with only 25% of full capacity, all the agents achieve their desired ones.

In all plots of Figures 6.26,6.27 and 6.28, the less is the value, best is the evacuation plan performance. Also, the evacuation plans (X axes) is ordered as function of ep_i, to be compared and the evacuation plan used in real life (ep_{ref}) is highlighted. We can observe that in most of the graphics (except for ad_i), the best evacuation plans are coherent if we compared ep results with

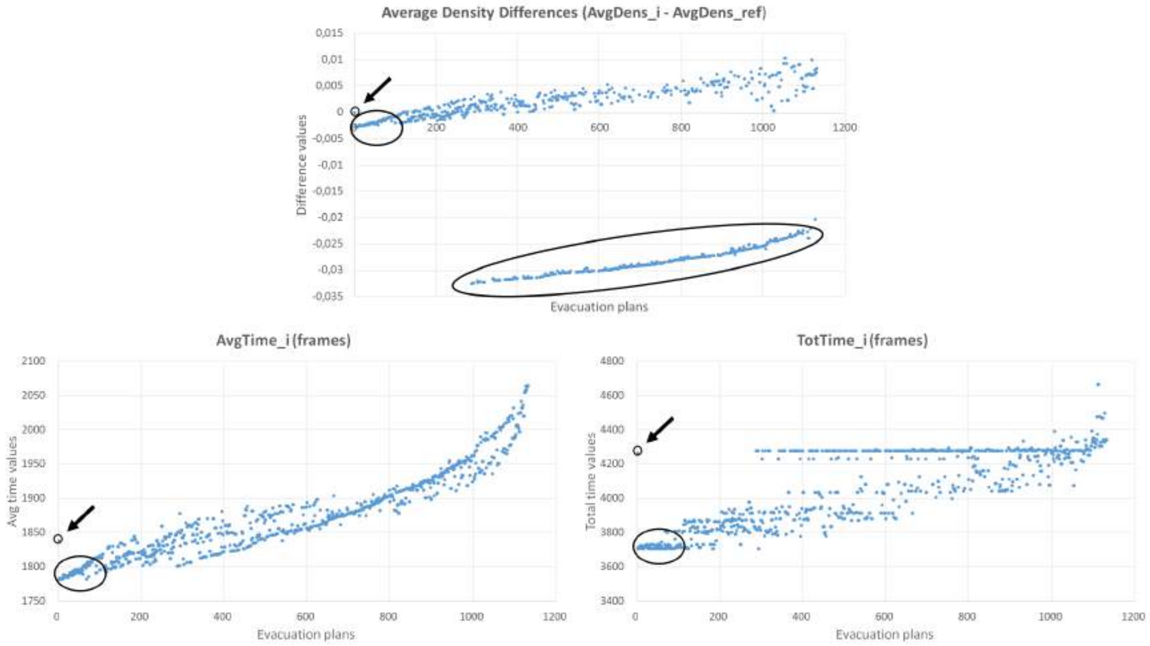


Figure 6.28 – On the top: difference between ad_i and ad_{ref}; on the bottom-left: obtained values of at_i and at_{ref} and in the bottom-right: difference between gt_i and gt_{ref}.

individual metrics. Even if the ad_i for best plans were not the best ones, the difference is very small and it does not change the final evaluation w.r.t to equation 4.6 (velocities are fixed, as mentioned before). In order to complement the analysis, we also included the plots considering the average and total time of simulation, without normalization (according to Equation 4.6), as illustrated in Figure 6.28. Again, the order is w.r.t to ep values for comparison. The conclusion is that even if one does not want to use ep metric, or include density and velocities, the best evacuation plans based on avg_time and $total\_time$ accorded to ep analysis.

As previous illustrated, the applied metric for ep calculation have showed coherency when compared to real-life data and also when the attributes are individually analyzed. It is important to mention that 240 agents do not provide a very dense crowd into the club, what can be observed based on densities data and the small differences obtained with the evacuation plans. A reasonable explanation is that with 240 agents, the environment has free space, so the densities and velocities are almost the desired ones. In order to accomplish with more interesting results, we did all analysis considering the full house (with 1010 agents).

6.3.2 Comparing evacuation plans of 240 and 1010 agents

After analyzing the data referring to real life experiment, we decided to repeat the experiment in order to check the club evacuation according a full house scenario. The local law, in night clubs, considers that full capacity is achieved when reached a distribution of $1person/m^2$. In this way, we considered the maximum population allowed in the night club equal to 1010 people, since the build area is $1010m^2$. Thus, we distributed a population of 1010 agents, according to club capacity, and re-simulated the 1331 possible evacuation plans. Table 6.7 summarizes the attributes of the 20 best plans for this scenario.

Plan_Id	Computed_ep	avgDensity	avgSpeed	avglifeTime	totalTime	pag	sup	$v4$
	(ep)	(ad_i)	(as_i)	(at_i)	(tt_i)			
741	1.73157	0.307902	0.781617	2669.95	5817	70	100	100
871	1.73268	0.314812	0.775104	2684.39	5663	40	100	90
1018	1.73434	0.313358	0.77818	2692.87	5694	30	100	90
817	1.73605	0.310867	0.78422	2728.78	5637	10	100	90
393	1.74295	0.309487	0.786974	2737.93	5770	100	100	70
857	1.74435	0.312966	0.780431	2711.95	5836	0	90	90
616	1.74497	0.307633	0.784451	2697.42	6002	100	100	100
182	1.74539	0.310426	0.781758	2694.41	5977	60	90	70
360	1.74563	0.312723	0.783084	2731.73	5795	70	80	80
952	1.74682	0.319379	0.773175	2714.13	5764	70	80	90
386	1.74763	0.309354	0.787275	2736.47	5879	80	100	100
786	1.74818	0.316327	0.775949	2706.76	5876	100	100	60
62	1.75131	0.311461	0.786662	2756.83	5840	60	70	100
600	1.75142	0.323631	0.769105	2710.19	5808	90	80	70
1108	1.75153	0.319389	0.777718	2744.11	5761	50	90	80
1020	1.75185	0.311845	0.782923	2723.25	5975	100	80	90
1237	1.75254	0.315411	0.779426	2728.09	5905	50	100	90
613	1.75271	0.321777	0.771718	2722.17	5817	80	80	60
811	1.75352	0.311845	0.781999	2715.64	6042	80	100	80

Table 6.7 – Statistical data of the best 20 evacuation plans considering 1010 agents.

Our first analysis aims to show the obtained difference between the two simulated populations, if we consider only ep values. We illustrate two curves representing the computed ep for 240 and 1010 people in order to compare both scenarios. For such experiments we have calculated the difference from the best plan ep to others 1330. Similar curves were obtained and are illustrated in Figure 6.29. As before, the X axes presents the evacuation plans ordered w.r.t computed ep, from the lower to higher for each population (240 agents in orange and 1010 agents in blue).

The observation of both curves comparing the difference between the ep from best plan to other plans allow us to verify a similar ascending pattern of evolution in both scenarios. It is interesting to mention that in full house simulations, the difference among the best plans (around 40 best plans) is larger if compared to the 240 agents' plans. We justify that because with full house capacity the environment is in the limit of its efficiency, so it is easy to identify clearly the best plans. It does not occur in scenarios with 240 people, where the evacuation plans present more similar ep values.

In a second branch of analysis, we compared the individual metrics when related to the best plans (respectively for 240 and 1010 agents). Figure 6.30 presents the difference and compares for the two groups of population the attributes of density (6.30(a)), speed (6.30(c)), average time (6.30(b) and total time 6.30(d)). Such attributes are, as previously defined, ranked according to ep values for each population.

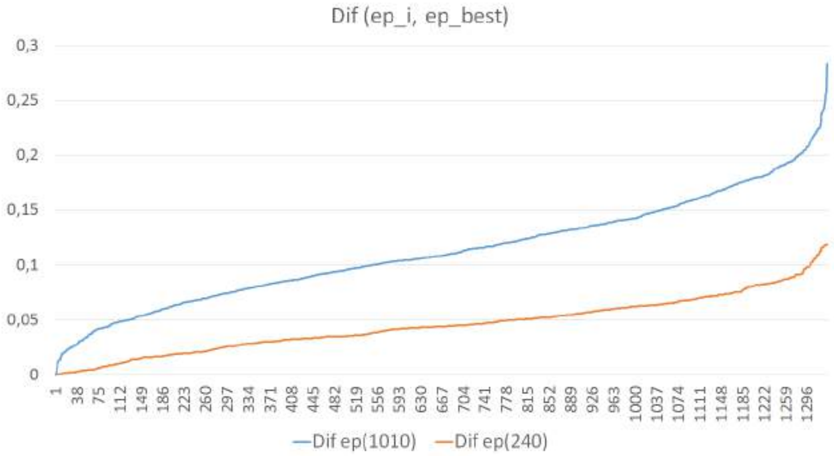
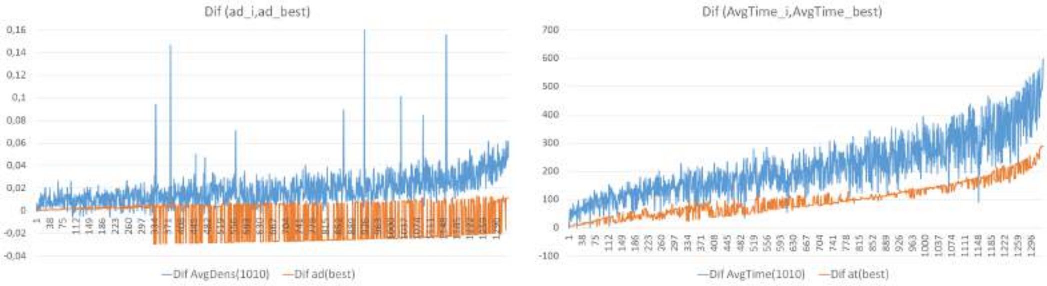
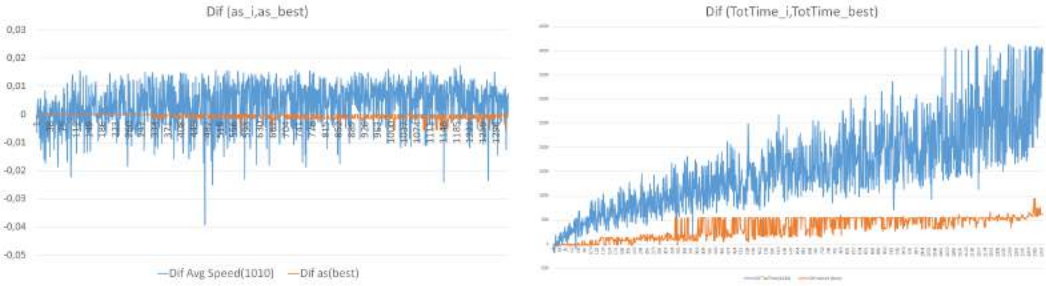


Figure 6.29 – Difference from best ep of each scenario to all other computed ep_i. Orange line illustrates the curve from plans of 240 agents while blue curve means plans of 1010 agents.



(a) Average density

(b) Average time



(c) Average speed

(d) Total time

Figure 6.30 – Independent comparison of attributes: average density (on the top-left), average time (top-right), average speed (bottom-left), and also the total time in both scenarios with 240 and 1010 agents (bottom-right).

It is possible to see in all simulations that the best plans for individual metrics are coherent with the ep computation. We believe this is a strong way to validity of ep metric. Moreover, it is easy to see that the environment capacity affects the metrics curves. Please, refers to 6.30(c) to verify that with 240 agents the speeds do not change too much, which indicates that people moves in almost desired velocity during the simulations.

Since all these simulations used fixed seed and speed, in the next section, we present some results obtained with random seeds.

Random Seeds:

Firstly, it is important to check the model dependence w.r.t. to pseudo-random computation. People initial distribution, speed variation (if speed is not fixed), routes to take during the evacuation process (if the plan is random) and time to wander throw a context (according to specified behavior). In the case of simulations previously discussed, speeds and bifurcations were fixed and the agents goals directly to their goals. In the current section, we want to evaluate the randomness of the process. Although it was a good idea to re-simulate all 2662 plans with at least 10 different random seeds, we discarded this possibility in this version of the work, due to the time needed to process (with only one seed - approximately 62 hours for 1331 plans with 240 agents and 185 hours for 1010 agents). So, we will need approximately 102 days processing data, without stopping. We, then, opted by simulating with 5 different seeds only the 20 best plans for 240 and 1010 agents. Furthermore we repeated these experiment 2 times, according to follow situations:

1. Random seed and fixed agents' speed in $0.8m/s$;
2. random seed and agents' speed.

Results of these simulations were compared with fixed seed, already described in lasts sections. After 400 performed simulations with random computation, Table 6.8 summarizes the obtained data and compare them with fixed seed. It is possible to observe that the average ep for best 20 plans is similar, and it is larger with 240 agents, since the plans result in similar data and it is difficult to guarantee the best ones. On the other hand, even re-simulating just the 20 best plans with 1010 agents, we claim for a certain confidentiality in the results obtained with with full capacity of the environment.

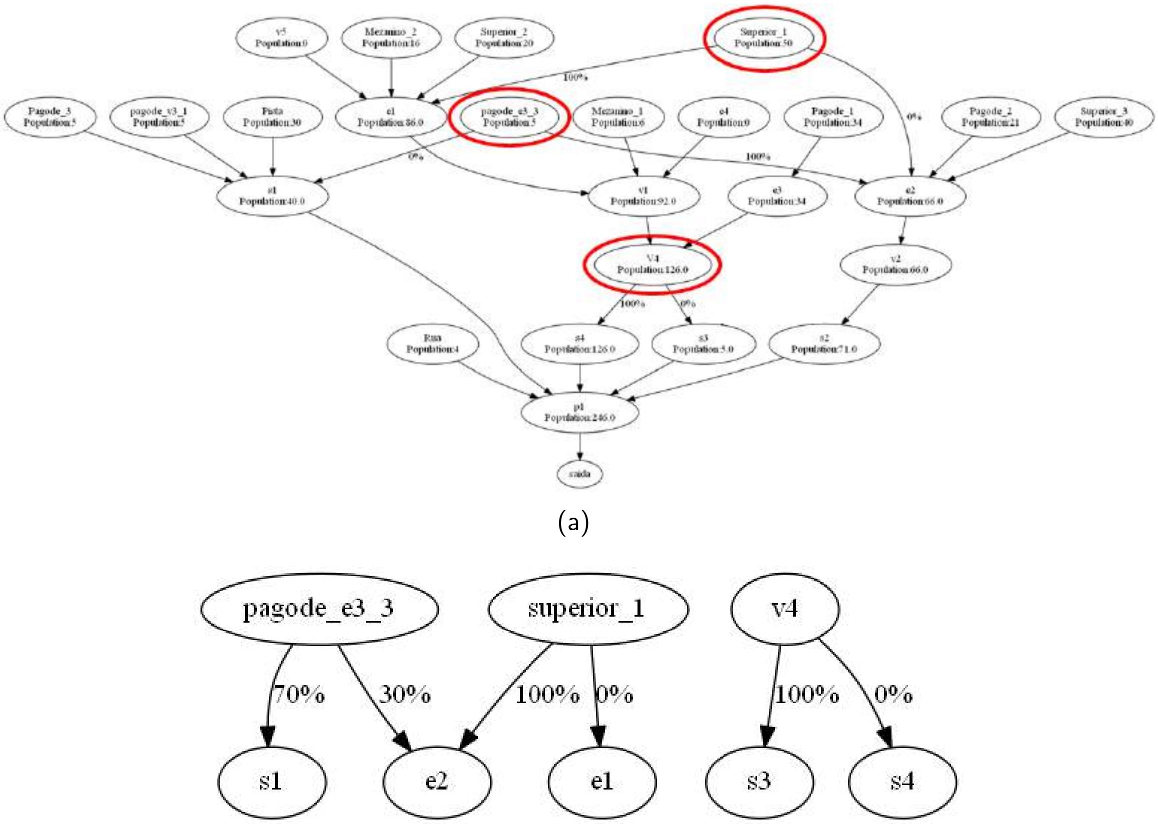
		1: Fixed seed/ Fixed speed	**2: Random seed/ Fixed speed**	**3:Random peed/ Random speed**	**Dif (1,2)**	**Dif (1,3)**
240 agents	*Ep Avg*	1.30926	1.2003401	1.28432338	0.108919	0.106669
	Ep Std Dev	0.000651	0.00887347	0.125460	0.008685	0.065205
1010 agents	*Ep Avg*	1.745951	1.7813688	1.763883	0.036874	0.105612
	Ep Std Dev	0.006449	0.0222178	0.144629	0.018705	0.091471

Table 6.8 – Summary of data obtained after performing 5 times each one of the 20 best plans from 240 and 1010 agents in 2 different situations, including the random computation. We also compare with fixed seed. The average ep in each situation is presented and the difference among such situations are also computed.

In next section we present a zoom in the evacuation plans with 1010 agents. The goal is to discuss the quality assessment of such evacuation plans, which has been, until this point, treated just with numerical metrics.

6.3.3 Studying Bifurcation Points in the Evacuation Plans

This section aims to perform quantitative and qualitative analysis of suggested routes for the evacuation plans, w.r.t 1010 agents' experiment. Figure 6.31(a) illustrates an example of an evacuation plan graph, generated automatically by CrowdSim. Three bifurcations where studied in order to compute the routes, as highlighted in the figure. Figure 6.31(b) shows the percentage of people directed to each possible route, when achieve a bifurcation during the simulations of egress. Ths sub-graph presented in Figure 6.31(b) describes the best of the 1331 evacuation plans (simulated with 1010 agents), already discussed in previous sections.



(a)

(b)

Figure 6.31 – Navigation graph of night club highlighting available bifurcations (a). The percentage of people which chose each possible route in the best simulated ep is illustrated in (b).

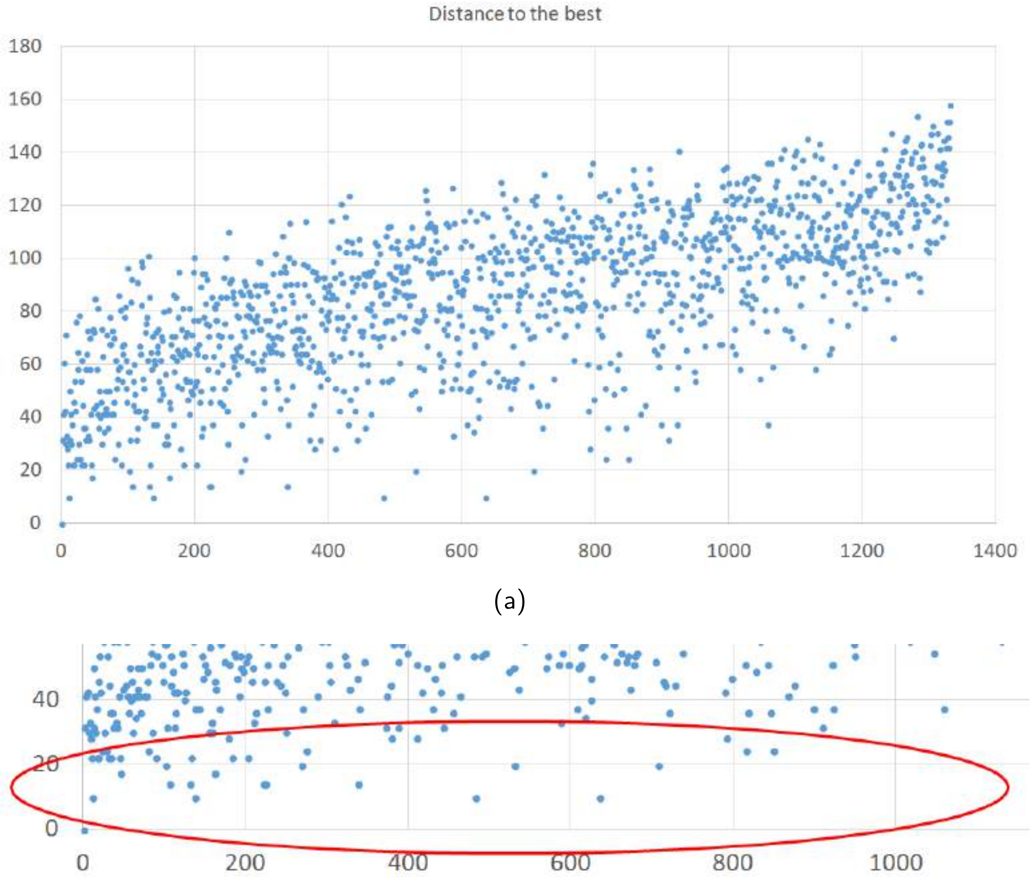
As previously illustrated we have worked with three bifurcations in the night club's environment. Next sections describe two studies: the first one is quantitative and aims to show the difference among the evacuation plans in terms of people distribution in the bifurcations; the second one is qualitative one which goal is to find out the assessment quality of best plans.

6.3.4 Quantitative Comparison among Evacuation Plans

In order to measure the similarity of the plans, we considered the used percentages in the bifurcations for each evacuation plan as a vector in $3D$ space formed by following components:

$(b1, b2, b3)$, where $b1$, $b2$ and $b3$ are related with left edges in the sub-graph of Figure 6.31(b), respectively PAGODE, SUPERIOR and V4. We called this vector $\vec{B_i}$ where i is related to the evacuation plan.

After we computed the vector $\vec{B}$, for all the 1331 computed plans, we computed the Euclidean distances from all $\vec{B_i}$ to $\vec{B_0}$ (the best evaluated ep). In Figure 6.32(a) we illustrate such distances values.



(a)

(b)

Figure 6.32 – Distance from all vectors $\vec{B_i}$ to $\vec{B_0}$, the best computed ep, based on bifurcation distributions (a). Some outliers plans are identified and highlighted in the down part of the graph (b). In both, X axis is ordered as a function of ep values.

Regarding the distance distribution from all plans to $\vec{B_0}$ it is possible to detect some outliers plans, as highlighted using a red ellipse, in Figure 6.32(b). Indeed, these plans are similar to $\vec{B_0}$ in terms of Euclidean distance if we only considered the distribution in the bifurcations, however they present higher values of ep, i.e. they are "worse" plans than $\vec{B_0}$. After having a look on these plans, we observed that such plans have generated higher values to ep because the attribute *totalTime* (of simulation) is also higher. So, in fact, they are similar plans (if compared with distribution in the bifurcations with the best plan), but they have higher ep values. We have studied 9 outliers plans in order to check this aspect based on the *totalTime* attribute. The difference of the *totalTime* based on such 9 studied plans are illustrated in Figure 6.33 where the first point is representing the *totalTime* according to the best plan.

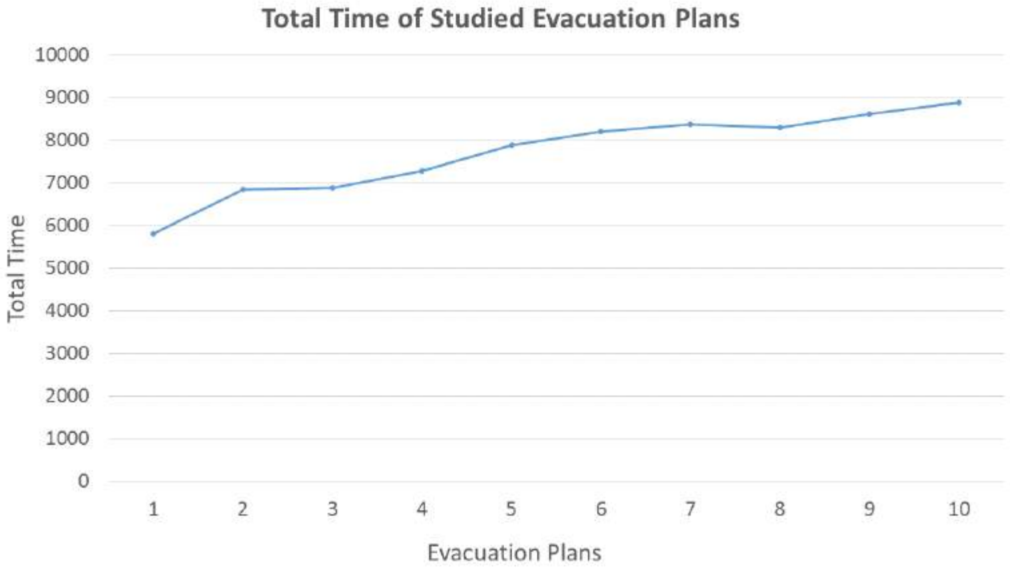


Figure 6.33 – Variation of the *totalTime* attribute for 9 outliers plans. The first point is illustrating the best plan.

6.3.5 Qualitative Assessment from Evacuation Plans Analysis

Considering the example of sub-graph in Figure 6.31(b), we studied the quality of the evacuation plans. Our main question was: "Is there any common sense behind the best and worst evacuation plans according to ep values?". So, after such analysis, one is able to informally answer if a certain evacuation plan is good or bad? Figure 6.34 shows the average ep values for some of the bifurcations percentage. For instance, it is easy to see that when the three bifurcations have higher percentage values to their left edges in the sub-graph, the ep values are lower (better). On the other hand, when the three bifurcations have lower percentage values to the left edges, obtained ep values are higher (worse scenarios). This graphic shows not only the obtained distribution, but also point out the best distributions to be used for taking decisions in a real scenario.

If we consider the 3 simulation scenarios firstly defined by the safety engineering people discussed in Section 6.1.5, we can observe that the best plan from these three also confirms the characteristics of the best plans. As illustrated in Figure 6.22 the best plan (on the top of the figure) presented more people being guided to the left edges in the sub-graph. It is important to highlight that "left" in this situation does not mean left in the physical space, but only to represent the lest edges in the sub-graph. In addition, to such analysis, we redraw the bifurcations to understand the exits associated to each decision and measure the travelled distance. Figure 6.35 shows a simple illustration of the graph nodes until people in the bifurcations achieve the exists (s1, s2, s3 and s4).

Table 6.3.5 presents traveled distances from the bifurcations nodes to the exits. In addition, we shown the best strategies according only the traveled distance and only the ep values. LetÂ´s

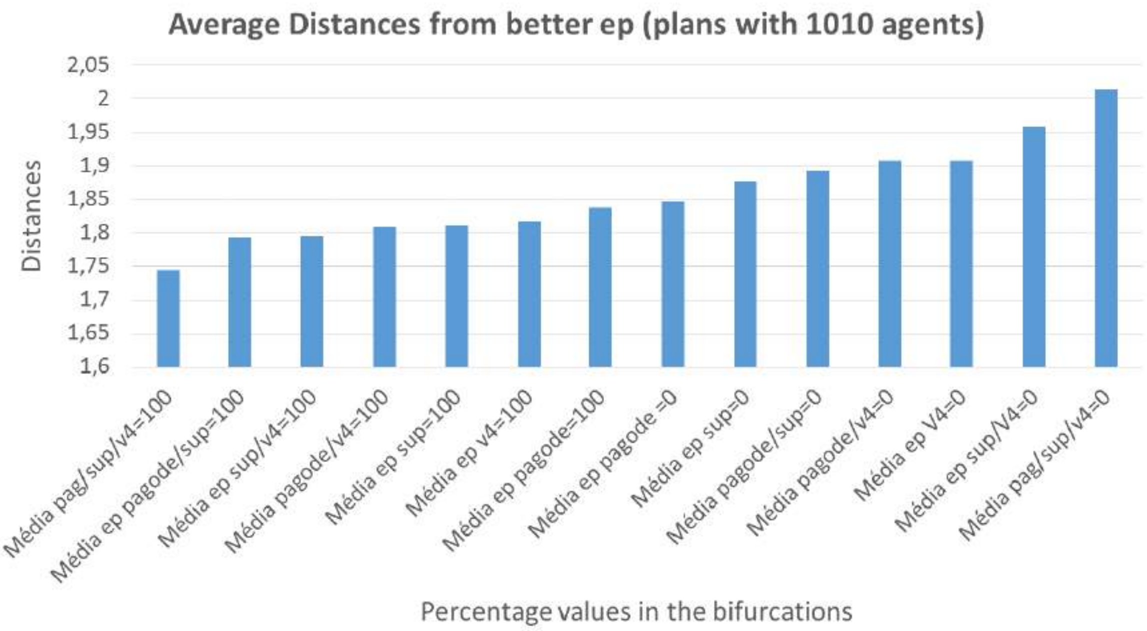


Figure 6.34 – Average ep values obtained for some main bifurcation configurations in simulations with 1010 agents. In the X axis the bifurcations distributions are ordered from the lower to higher value of obtained average ep.

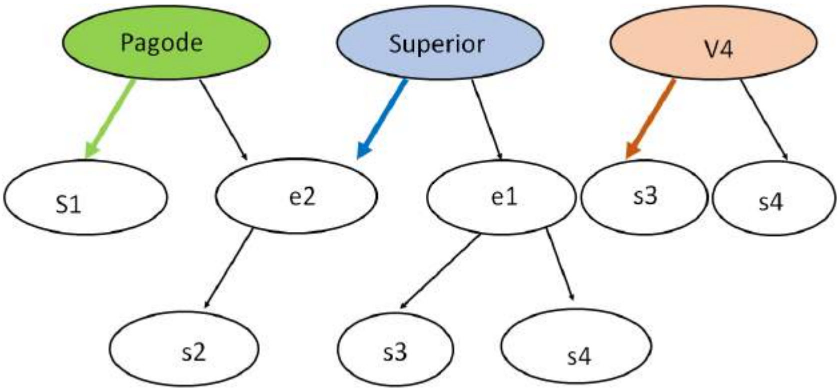


Figure 6.35 – Redraw of bifurcations showing the sub-graph nodes until the exits.

consider the best evacuation plan with 1010 people (from 1331 with granularity of 10% the best plan has id=741), which main characteristics are: $\vec{B}_{741} = (70, 100, 100)$ and $ep_{741} = 1.7315$. If we use such percentages in Figure 6.35 (again, such values are related to the left edges in the sub-graph), it is easy to see that this evacuation plan suggest that exit $s4$ is going to be empty. This is explained by Table 6.3.5, but it also emerges from the doors dimensions (in meters): $s1 = 1.77m$, $s2 = 1.15m$, $S3 = 1.14m$ and $s4 = 1.01m$. In addition to be related with the higher traveled distance, the $s4$ is also the narrow one. People in the other doors for evacuation plan id=741 are: $s1 = 266$, $s2 = 319$, $s3 = 415$ and $s4 = 0$.

To provide comparisons, we included the analysis if the worst scenario for 1010 people. It is the evacuation plan id=936 and characteristics are: $\vec{B}_{936} = (0,0,0)$ and $ep_{741} = 2.0149$. People in the other doors for evacuation plan id=741 are: $s1 = 245$, $s2 = 240$, $s3 = 0$ and $s4 = 515$. So, we can see as the worst evacuation plan used the highest path with almost 50% of total population. In addition, we present the following comparison: *i)* $tot\_time_{741} = 5817$ frames, while $tot\_time_{936} = 9757$ frames; *ii)* $avg\_time_{741} = 2669.95$ frames, while $avg\_time_{936} = 3266.28$ frames and *iii)* $avg\_density_{741} = 0.3$, while $avg\_density_{936} = 0.37 person/m^2$.

Strategies	Traveled distance	Best strategies according to ep metric	Best strategies according to distance	Worst strategies according to ep metric	Worst strategies according to distance
Superior-e1-S3	62,3097			X	X
Superior-e1-s4	67,1534			X	X
Superior-e2-s2	37,2866	X	X		
V4-s3	33,3201	X	X		
V4-s4	37,9206			X	X
Pagode-s1	59,4239	X			X
Pagode-e2-s2	33,9236		X	X	

Table 6.9 – Evaluating Navigation Strategies in the Night Club.

6.3.6 Generalization of Best Evacuation Plans

Figure 6.34 showed average ep values for some main characteristics of evacuation plans considering 1010 agents, represented by the three existing bifurcations. One aspect we want to evaluate was the generalization of best plans, i.e. the best plans when simulating with 1010 agents can be generalized in someway for different populations? Then, we plotted the same graphic of Figure 6.34 however considering 240 agents, so we can evaluate their coherency. The evacuation plans which put more agents in left edges in the three bifurcations present lower values of ep, as also presented in Figure 6.36. As can be seen in the two figures, the best evaluated plans are in general coherent and described by higher percentages in the studied bifurcations.

In addition, we evaluated in which positions the best plans of 240 scenarios were ranked in 1010 and also the opposite. Table 6.10 summarizes this analyzes in both scenarios.

When analyzing such comparison of scenarios it is clear the advantage taken by the 1010 plans when applied in the scenario of 240 agents. In order to evidence this, we calculated the average position of the 20 best plans in each scenario. From 1331 possible positions, the average of plans from 240 scenarios when ranked with 1010 plans is **218.45** while the position of average of 1010 on 240 scenario is **99.9**. So, with these numbers we claim again that the full capacity of the environment should be used to evaluate the evacuated plans.

The data analysis discussed so far aims to validate the ep metric as a reasonable way to evaluate evacuation plans. So, we are able to find the best ones, to measure their dependence on randomness process and conclude also that a full capacity environment is the best choice to provide evaluations.

6.3.7 Final Considerations about Evaluations in the Night Club:

We have some interesting comments to describe about our analysis. Firstly, we shown that our metric ep makes sense and can maybe used to chosen a good (or the best) evacuation plan. We also found evidences that the best analysis have to be made with the full capacity of the environment.

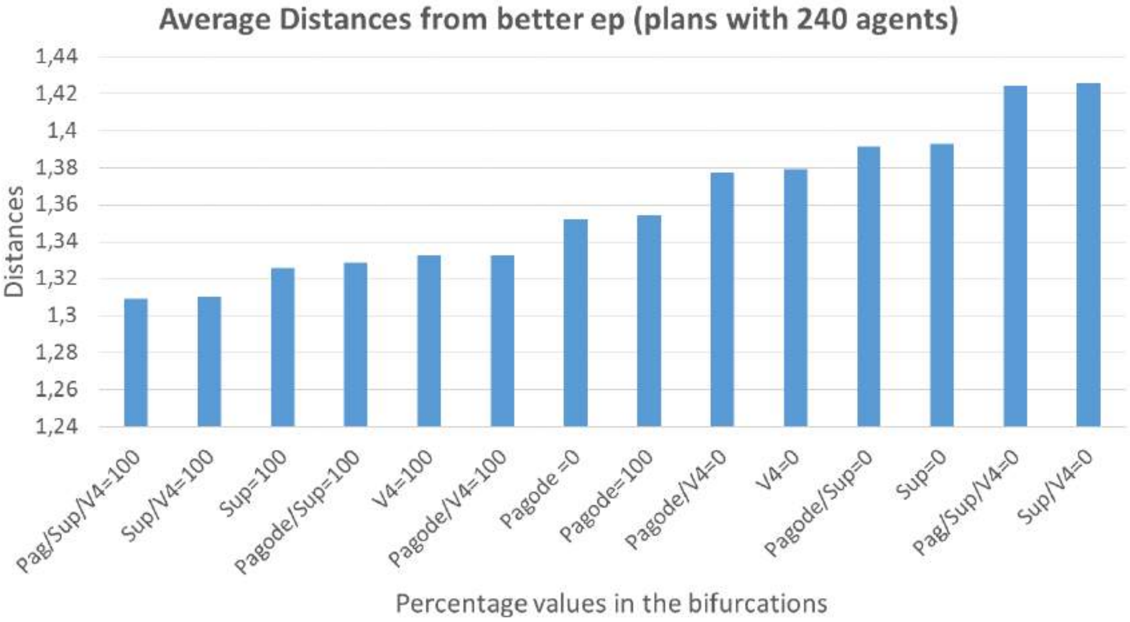


Figure 6.36 – Average ep values obtained for some main bifurcation configurations in simulations with 240 agents. In the X axis the bifurcations distributions are ordered from the lower to higher value of obtained average ep.

It is certainly a common knowledge, but we liked the fact that we found numerical evidences (see Figure 6.29). We have the evidences that best plans can be generalized to different crowd densities, as shown in Section 6.3.6.

Another consideration is that the short path is not always the best way to evacuate an environment, even if it is a good initial guess. The similar plans, in terms of people distribution in the decision points, not necessarily have similar results in terms of obtained output. As previously discussed, total time of simulations can be very different even in similar evacuation plans. Although this is true, there are some logic behind the best evacuation plans, numerically showed through traveled distances and doors dimensions. So, maybe having much less than the 1331 simulated plans we can find a very good evacuation plan. We can, for instance, simulate some of cases as illustrated in Figures 6.34, 6.36 and select only the best scenarios to simulate similar distributions, increasing their granularity.

Regarding other crowd simulators, we claim that our evacuation plans and mainly our metric to evaluate them can be tested with any simulator. More specifically, the scripts to generate and evacuate plans can be easily integrated with any crowd simulator. The only restriction is that the simulator has to generate positions of each person at each time, as the output generated by CrowdSim.

Of course, a priori, all these comments are true only for the night club environment, with a population of 240 or 1010 agents and with the specific tested people distribution in the creation contexts. The only variable was the people distribution in the bifurcations nodes. It is certainly a future project to explore more data in different environments, with different distributions, populations,

Best in 240	**Order in 1110**	**Best 1010**	**Order in 240**
1209	241	741	80
1327	474	871	14
385	324	1018	40
706	208	817	47
1132	668	393	109
322	132	857	31
1203	103	616	11
1289	30	182	96
48	707	360	130
386	11	952	106
616	8	386	10
1094	65	786	182
592	106	62	365
871	2	600	271
1237	17	1108	99
520	32	1020	67
176	34	1237	15
272	212	613	123
1196	792	811	26
326	203	1097	176
Average	**218.45**		**99.9**

Table 6.10 – Comparison of 20 best plans positions in 240 and 1010 ranks.

behaviors, among other possible variables.

7. FINAL CONSIDERATIONS

People, when part of a crowd, are able to perform unusual behavior, which would not be performed by a single person [48]. A crowd is a powerful entity and its understanding is very important, mainly in what care about safety issues. The understanding of crowd motion is an important source of knowledge in order to map its features and behaviors that can influence, among other aspects, the efficiency of the environment where the crowd evolves.

By simulating crowds, engineers can validate its behaviors and evolution into a specific environment according to different circumstances and constraints. Furthermore, companies can save money and time when simulating and analyzing crowd behavior during buildings design phase.

The problem addressed in this thesis was concerned with simulating the egress process in order to investigate the best way to a crowd leave an environment. In order to attend this issue, we presented *CrowdSim*, a framework to simulate crowds in different situations during an evacuation process.

We know that it is very important the coherency on data computed by crowd simulators. Since we want to use simulation results to improve aspects in real life, this validation is an important issue. We evaluate our framework according to international guidelines [41] and recognized scientific approaches [27]. A set of tests have been performed in different categories aiming to check the accuracy of results computed by *CrowdSim*. Our framework have shown acceptable results in all the tested categories.

Considering *CrowdSim* as a validated tool, we have applied it on a set of case studies. As the principal we can consider the case studies developed in a night club, a college building and a school. Such cases have been detailed in this thesis but other cases have also been developed [74]. The goal of the case studies were to estimate the behavior of a crowd, considering aspects of comfort and safety, in different environments. Several projects were performed and in some of them we had the opportunity to compare simulated data against information captured from real life evacuation exercises.

The case study performed in the night club can be considered as substantial to the proposed goals of this thesis. Such case has allowed us to collect data from a real life evacuation exercise. Indeed, safety engineers have used our framework to define an evacuation plan to be used during the real evacuation exercise.The first defined evacuation plan, specified by the engineers, when simulated in CrowdSim, taken approximately 5 minutes. In addition, this first plan have shown some specific attention points that were observed by the safety team and new evacuation plans were proposed. Two of new plans, when simulated, predicted a evacuation process in 142 and 147 seconds, respectively. The best of them, considering the total time for evacuation, was then applied by the safety team during the night of the real exercise and make the real people leave the night club in 175 seconds. This aspect was considered a quantitative evidence about the accuracy of *CrowdSim* results and validates our research approach. Furthermore, other aspects were evaluated as density, speeds and etc, as discussed in this work.

After the success of the night club exercise, we were even more motivated to follow our goal: to investigate how to automatically generate the best plan to be performed in a specific environment. The night club was considered as a benchmark in this work, since we know information from a real life scenario. We developed an approach to generate a set of evacuation plans, able to be performed in the studied environment (the night club). In addition, in order to achieve our goal, we developed a metric, ep able to calculate the level of efficiency of an evacuation plan. Such metric has allowed us to automatically evaluate all the possible plans for the night club, in order to rank them.

Our ep metric is an aggregation of different factors and obtained results show its coherency, as discussed in Section 6. This is a very important contribution of our work, which allow us to evidence some aspects:

1. The short path for a people leave a building is not necessarily the best one;
2. Plans with more people should be used to quantitative analysis and will also show good performance for situations where the number of people is lower. Our conclusion is that in a sparse environment, many evacuations plans present similar results in terms of obtained metrics. In the same time it is difficult to say which density is the best to compute ep. We have used density as $1p/m^2$ in the spaces, as the higher allowed density;
3. Evacuation plans that are similar in terms of people distribution in bifurcations are not necessarily similar in their results: our simulations show that environment attributes, such the doors size and distances until achieve exits are many important characteristics and can change the efficiency of a specific evacuation plan.

It is important to highlight that the project in the night club has allowed us to evidence our hypothesis. But, similar investigations in other environments must be performed, in order to really achieve concrete conclusions about observed evidences. One important aspect, even if we only used ep in the night club is that all results were coherent and it is important for the continuity of this work.

While only the simulation in the night club used the ep metrics, the case study performed in an elementary school, was very important as well. It made us to reflect about an important, but no very well observed aspect: *Usually crowd simulation data provide important information for building managers. But, how can we make this information interesting to the students, the more important people form a school?* This challenge has motivated us to develop *Game4Safety*. Such game was developed with goal to provide an interactive way for the students to analyze obtained data of performed simulations. Diverse play test sections were performed and the feedback form the students about the subject was very positive. We believe that training people is an important tool to prevent injuries and also to contribute to development of a culture of safe. Also, the use of game-based approach can engage people in the process, helping them to develop and share important information in the safety field. It is sure that the developed game, currently in use at the school, can improve the students engagement in the training process concerning building exploration and evacuation.

As far as we know, our research is very original in Brazil. *CrowdSim* is recognized as the first Brazilian Crowd Simulation Software. Such fact has motivated the insertion of *CrowdSim* in Brazilian Press many times, including the website of Brazilian Federal Government (please see appendix B.3. In addition, in 2013, we submitted *CrowdSim* to Santander Universities Prize[1] and among thousand of projects from all around Brazil we get the first place due to the project contribution to Brazilian Society. Such awards recognizes the work from researchers of different fields and give to Professor Musse, coordinator of the project, for the first place in the category of *Innovation Technology* (details are available in Appendix B.4).

7.1 Future Work

In this thesis we worked with evacuation scenarios. Some future directions should be focused on usual situations as developing and validating mobility and occupation plans. We are interested in understanding different patterns that a crowd can present when populating a place. On the other hand, which kind of aspects can affect the way in a crowd evolve in the environment.

In addition, we summarize a set of future work that can contribute to our research:

- *Concerning evaluation*: we intend to propose more interactions with the safety engineers, so they can help with quantitative and qualitative aspects.

- *Other factors*: We are interested in dealing with other factors that can impact the crowd evolution. Such factors can include, no exclusively, aspects of fire, smoke and other factors able to affect agent state.

- *Traffic*: We know that when in a outside area, people need to respond to the cars evolution and this highly impact their motion with respect to desired path versus the real walked path.

- *Virtual Signage*: Explore the way how the application of virtual signage can affect the motion of the agents.

- *Opposing Groups*: How to deal with distinct crowds that evolves in the same environment? The goal, in this aspect, is concerned with groups or even crowds which require separation or specific guidance through the environment (e.g. two distinct groups of football supporters).

- *The optimal evacuation plan*: In this thesis we generate a set of plausible plans end investigate all of them in order to identify the most appropriated. We can consider this point as the most promising future work: the idea to decrease the number of plausible plans until be able to generate only **the best** plan according some specific environment.

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[1] `santanderuniversidades.com.br/premios/`

7.2 Other Correlated Topics

During the evolution of the Ph.D., we have worked with some correlated subjects. Next, we described some of them:

7.2.1 PhD. Qualifying: Crowd Comparison

For the PhD qualifying, we developed an approach to compute crowd features that could be used to compare them [54]. In this work, we developed a model to quantitatively compare global flow characteristics of two crowds. The developed approach explores a 4-D histogram that contains information on the **local velocity** (speed and orientation) of each spatial position, and the comparison is made using histogram distances. The 4-D histogram also allows the comparison of specific characteristics, such as **distribution of orientations** only, **speed** only, **relative spatial occupancy** only, and combinations of such features. Experimental results have showed that the proposed quantitative metric correlates with visual inspection.

7.2.2 Visiting Student

During the first semester of 2013 I had the opportunity to be supervised by Professor Norman Badler, as a Visiting Student at University of Pennsylvania. During that time we have worked in a project concerned with animation gaze [55]. Despite the fast-growing richness of virtual worlds, the majority of interactions between the player and non-player characters (NPCs) still remain scripted. In this project we developed an approach using NPC's animations to reflect how they feel towards the player and as a proof of concept, investigate the potential for a straightforward gaze model to convey trust. Through two perceptual experiments, we find that viewers can distinguish between high and low trust animations, that viewers associate the gaze differences specifically with trust and not with an unrelated attitude (aggression), and that the effect can hold for different facial expressions and scene contexts, even when viewed by participants for a short (five second) clip length. With an additional experiment, we explore the extent that trust is uniquely conveyed over other attitudes associated with gaze, such as interest, unfriendliness, and admiration.

7.2.3 Detection and Classification of Change Behavior in Human Crowds

We have collaborated with professor Cláudio Jung[2], from Federal University of Rio Grande do Sul, during the year of 2015. The main goal of the collaboration was to explore *CrowdSim* possibilities in order to simulate change behaviors. In usual conditions, the crowd moves in an orderly manner, but panic situations may lead to catastrophic results. By the application of dynamic behaviors in *CrowdSim*, we provided a set of different situation of change behaviors. The general goal of Professor Jung's project was to develop a method able to identify change behaviors in human crowds using computer vision. The developed approach can identify global changes, by evaluating

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[2] `inf.ufrgs.br/~crjung`.

2D motion histograms in time, and also locally, by identifying clusters that present similar spatial locations and velocity vectors. The method was tested on publicly available datasets involving crowded scenarios, and also on synthetic data produced by *CrowdSim*, which allows the creation of controlled environments with known behavior. Results of this project have generated a paper that was submitted to IEEE Transactions on Circuits and Systems for Video Technology[3]. The paper is currently under review process.

7.2.4 Book Proposal

The content of this theses is part of a book proposal. The book is being developed in partnership with Professors Soraia Musse and Cláudio Jung. We are currently in contact with Springer[4] in order to organize the publication.

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[3] `ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=76.`

[4] `springer.com`

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A. CONFIGURATION XML

This appendix presents a XML file computed by *CrowdSim* representing a scenario to be simulated. The file contains all the information defined in the configuration module and that serve as input to the simulation module.

```xml
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            <posz>-1206.15</posz>
        </vertex>
        <vertex idVertex="1">
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        </vertex>
        <vertex idVertex="2">
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            <posx>-1232.29</posx>
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            <posz>-1198.24</posz>
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            <refVertex2>1</refVertex2>
        </edge>
        <edge idEdge="1" activateDoor="no">
            <refVertex1>1</refVertex1>
            <refVertex2>2</refVertex2>
        </edge>
        <edge idEdge="2" point1="0" point2="1" activateDoor="yes" canClose="no" refContext1="2"
        refContext2="0">
            <refVertex1>2</refVertex1>
            <refVertex2>3</refVertex2>
        </edge>

    </edges>
    <contexts>
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        OtherRegionFinalTime="0" OtherRegionInitiallTime="0" PercentualFindOtherRegion="0"
        PercentualStayInRegion="0" PercentualRemoved="0" FinalTimeGroupCreation="2"
        InitialTimeGroupCreation="1" bac="0" AgentsColor="amarelo" framesAux="0" idContext="0"
        isDecisionPoint="true" contextName="pista s1 7" percentualOfDrunks="0"
        initialCreationTime="1" regionType="2" totAgents="5">
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            <refEdge>2</refEdge>
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            <refEdge>44</refEdge>
```

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            <refEdge>134</refEdge>
            <refEdge>135</refEdge>
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    <DynamicBehaviors />
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B. Press releases about *CROWDSIM*

The results of some projects performed with *CrowdSim* appeared in Brazilian News. In this appendix we present some press releases that published about *CrowdSim*, specifically for some projects (in portuguese):

B.1 Stadium

B.2 School

B.3 Brazilian Government Website

B.4 Santander Prize

29/01/2013 16h31 - Atualizado em 29/01/2013 16h44

Bota investe para tornar o Engenhão um estádio moderno e seguro

Estudo feito por faculdade gaúcha aponta que é possível a total evacuação do local em apenas seis minutos e meio com um público de 47 mil pessoas

Por **Fred Huber**
Rio de Janeiro

A tragédia em Santa Maria, no Rio Grande do Sul, onde 231 pessoas morreram após um incêndio em uma boate, sensibilizou o Brasil e iniciou uma série de discussões sobre segurança em locais que recebem grandes públicos. No esporte não é diferente, já que os locais de competição recebem constantemente multidões. No Engenhão, **um dos mais modernos estádios do país**, o Botafogo tem tentado se cercar de cuidados para que não ocorram grandes problemas.

Soraia Musse, Capitão Fabiano, Sergio Landau e Alex Busquet (Foto: Fred Huber)

O diretor geral Sergio Landau contou que o clube contratou uma equipe da PUC-RS para desenvolver um estudo sobre as condições de segurança do estádio. O resultado foi positivo. O Engenhão tem sido palco de testes feitos pelo comitê organizador da Copa de 2014.

- A tragédia não foi fato motivador, mas mexe com nosso íntimo. Isso já é uma preocupação antiga nossa, as questões de segurança são vistas constantemente. Nosso estádio é moderno, aprovado pelo COI em termos técnicos e de todo sistema de segurança de evacuação. A capacidade é de 45 mil, e para as Olimpíadas será ampliada para 60 mil. Limitamos a 42 mil pessoas em grandes eventos. Contratamos o trabalho da PUC-RS assuntos voltados para segurança. Os estudos demonstraram que o estádio tem todas as condições.

De acordo com Soraia Musse, professora da PUC-RS e responsável pelo trabalho, foram feitas diversas simulações, por exemplo, para o caso de necessidade de evacuação do estádio caso aconteça alguma grande ameaça aos torcedores. Ela afirmou que em todas as possibilidades analisadas o resultado foi bom. De acordo com o estudo, em apenas seis minutos e meio é possível evacuar o Engenhão lotado, com quase 47 mil pessoas.

- Nós desenvolvemos pesquisas de simulação de multidões. Reconstruímos no computador e, a partir daí, desenvolvemos as simulações em todos os tipos de cenário, como, por exemplo, com saídas abertas ou fechadas. Medimos o tempo de evacuação para 47 mil pessoas e deu seis minutos e meio, o que é um tempo bom. Depois fizemos com a saída em caracol fechada e tivemos o tempo de sete minutos. Na medição de densidade de pessoas por metro quadrado, nunca apareceu um número perigoso.


Engenhão tem sistema de monitoramento com câmeras (Foto: Globoesporte.com)

De acordo com Alex Busquet, médico-chefe do Engenhão, os cuidados para que os torcedores tenham uma boa assistência médica também são rigorosos. Segundo ele, o clube trabalha sempre com uma oferta maior do que é considerada a mínima. Normalmente o estádio conta com quatro ambulâncias e três postos médicos.

- Disponibilizamos condições acima das que são consideradas mínimas, de acordo com a expectativa de público. Fazemos o atendimento pré-hospitalar e levamos para o hospital, caso seja necessário. No Engenhão, a circulação das ambulâncias pode ser feita em qualquer um dos níveis, e com rapidez. Temos quatro ambulâncias com UTI móvel e três postos médicos. Cada ambulância tem médico, enfermeiro e condutor especial com curso de primeiros socorros.

O Capitão Fabiano, do Gepe, grupamento especial de policiamento em estádios, o Engenhão atende a todos as exigências sobre a segurança dos torcedores. Ele disse que a PM tem a preocupação de monitorar a movimentação das torcidas, principalmente as organizadas, no entorno das praças esportivas.

- Obedecemos a legislação de grandes eventos esportivos. Hoje o Engenhão apresenta aprovação total, não há problemas de segurança. Existe o laudo dos Bombeiros, do CREA e da Vigilância Sanitária também. Fazemos análise quantitativa e qualitativa do público e vemos os riscos em até 5 mil metros de entorno do estádio. Analisamos vias de acesso e rivalidade de torcidas organizadas, que são acompanhadas desde a concentração até a dispersão após os jogos. Tem dado resultado, temos o controle total. Cada jogo é uma história e tem os seus riscos.

O consumo de bebidas no entorno é considerado pelo policial um grande problema para o policial, já que as pessoas tendem a entrar no estádio nos 15 minutos que antecedem o início das partidas, o que gera confusão por causa da grande concentração. Ele acredita que o melhor seria fazer a comercialização dentro dos próprios estádios.

29/09/2014 07h10 - Atualizado em 29/09/2014 07h10

Jogo de videogame desenvolvido no RS pode ajudar a prevenir tragédias

Programa simula evacuação de espaços em situações de emergência.
Segundo criadores, programa também pode detectar falhas em prédios.

Do G1 RS

Jogos de videogame costumam prender a atenção de crianças, adolescentes e até mesmo de adultos. Pensando nisso, pesquisadores da Pontifícia Universidade Católica do Rio Grande do Sul (PUCRS), desenvolveram um projeto pioneiro no país que pode ajudar a prevenir tragédias, como mostra a reportagem do Teledomingo (veja o vídeo).

Trata-se de um jogo de videogame que simula a evacuação de espaços em situações de emergência. O tema ganhou ainda mais atenção depois da tragédia da boate Kiss, em Santa Maria, atingida por um incêndio em janeiro do ano passado que resultou na morte de 242 pessoas e deixou centenas de pessoas feridos.

"O evento específico lá de Santa Maria serviu como um alerta, tanto para instituições, que buscaram solucionar problemas de segurança que elas têm, como também para o poder público, que buscou uma qualificação e uma preocupação em acompanhar as instituições e saber se elas têm as condições mínimas de segurança", diz o diretor do colégio Pastor Dohms, Stanlei Braun, uma das escolas que aderiu ao projeto.

O programa está sendo desenvolvido por um grupo de pesquisadores da PUC de Porto Alegre que estuda simulação de multidões. Nestes casos, o comportamento das pessoas muda, segundo os pesquisadores. "Os valores que as pessoas têm como ser humano, em determinados momentos são abandonados e o valor e grupo é maior e faz com que a pessoa passam a ter um comportamento diferenciado. E o ambiente também tem que atender e ser seguro para isso", diz Vinicius Cassol, doutorando em ciências da computação na universidade.

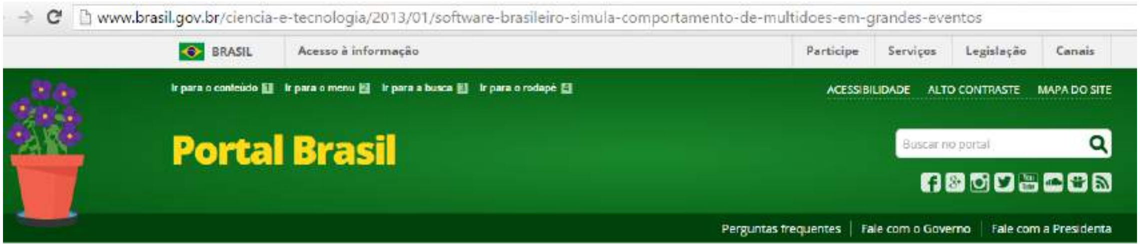

Jogo treina alunos para encontrarem melhor rota de saída em caso de emergência como um incêndio (Foto: Reprodução/RBS TV)

Para preparar melhor os alunos de uma escola para deixar o local rapidamente em caso de emergência, a solução foi fazer do treinamento um jogo de videogame. O programa reproduz com total fidelidade todos os ambientes da escola. Assim, em caso de incêndio, por exemplo, qualquer pessoa deverá saber encontrar a melhor rota de saída.

"A ideia que nós tivemos foi mostrar como funciona a simulação de emergência dentro de uma escola para as crianças, foi apresentar isso através de um game. As crianças vão jogar, vão verificar: 'Ah, eu saio por aqui, essa aqui é a escada que eu devo pegar", explica a professora da Faculdade de Informática da PUCRS, Soraia Musse.

A turma de um colégio de Porto Alegre foi ver de perto o novo projeto de segurança da escola. E aprovou a brincadeira. "Eu ia conseguir me guiar na escola, nos corredores, escadas, me achar bastante, comparando com o videogame. Até ajudando outras pessoas", diz o estudante João Gabriel do Amaral, de 14 anos.

Além de mostrar a melhor rota, o programa vai servir de modelo para adaptações que precisem ser feitas na estrutura dos prédios. "Nós vamos conseguir trabalhar preventivamente, ou seja, nos vamos conseguir instruir todo o grupo de profissionais da instituição e trabalhar em cada sala de aula esse planejamento. Nós vamos conseguir, inclusive, dizer com exatidão, quanto tempo de cada ambiente o aluno vai levar do seu local ate chegar no ponto onde tenha uma saída de emergência", conclui o diretor da escola.



www.brasil.gov.br/ciencia-e-tecnologia/2013/01/software-brasileiro-simula-comportamento-de-multidoes-em-grandes-eventos

CIÊNCIA E TECNOLOGIA

Software brasileiro simula comportamento de multidões em grandes eventos

O CrowdSim possui o diferencial de poder realizar análises mais complexas, que levam em consideração diferentes situações, inclusive eventos de pânico e emergência

Finep

Software CrowdSim constrói simulações em 3D dos locais dos eventos

Grandes competições esportivas e espetáculos artísticos costumam reunir centenas de milhares de pessoas, seja em ambientes fechados, como estádios e casas de shows, seja em espaços abertos, como praias e praças públicas. Para ajudar a prevenir incidentes nessas ocasiões, como o ocorrido recentemente em Santa Maria, o Laboratório de Simulação de Humanos Virtuais da Pontifícia Universidade Católica do Rio Grande do Sul (PUC-RS) desenvolveu um software inédito no Brasil, capaz de simular o comportamento de multidões.

Em média 10 vezes mais barato que concorrentes internacionais, o CrowdSim possui ainda o diferencial de poder realizar análises mais complexas, que levam em consideração diferentes situações, inclusive eventos de pânico e emergência. Também é possível analisar os diversos perfis de público e como reagem, por exemplo, idosos, crianças e pessoas com dificuldade de locomoção. “As soluções estrangeiras não são capazes de lidar com essas particularidades”, explica a coordenadora do projeto, Soraia Raupp Musse.

O indivíduo sozinho, em geral, toma decisões mais sóbrias, mas, na multidão, passa a fazer parte de uma massa com vontade própria e às vezes desordenada. Por isso, a solução foi programada para levar em conta o percentual de pessoas que tomam decisões caóticas, como aquelas que não se dirigem para uma saída por um motivo qualquer, por ter desmaiado ou entrado em pânico, por exemplo.

Em 2000, o comportamento de multidões foi alvo da tese de doutorado da professora Soraia, que desde então se debruça sobre o tema. “A ferramenta reúne o resultado de todos esses anos de pesquisa”, revela. O desenvolvimento técnico do software foi realizado em um ano e meio e custou cerca de R$ 200 mil, recursos que foram aportados pela Finep, empresa pública vinculada ao Ministério da Ciência, Tecnologia e Inovação. O produto foi apresentado em novembro do ano passado e, com a proximidade da Copa de 2014 e das Olimpíadas, ganhou destaque na área de tecnologia aplicada à segurança.

O próximo passo é firmar acordos comercias com empresas interessadas em levar a solução para o mercado. Soraia revela que está analisando propostas e espera, já em março, estar com as parcerias consolidadas. “A Copa do Mundo de 2014 é uma grande oportunidade e não queremos deixá-la escapar. Nossa meta é que o CrowdSim seja usado em todos os estádios sede”, diz a professora.

A ferramenta já foi testada no Estádio Olímpico João Havelange, mais conhecido como Engenhão, no Rio de Janeiro. Um especialista em modelagem construiu animações em 3D que reproduziram em detalhes o estádio, o que foi feito a partir de um levantamento prévio de dados que considerou as características da estrutura física, plantas e imagens fotográficas do ambiente, informações sobre a localização de portões, escadas, banheiros, corredores e outras áreas de circulação, além da capacidade de lotação e ocupação durante os jogos.

Fonte:
Financiadora de Estudos e Projetos

CrowdSim leva prêmio de inovação

Leandro Souza // quarta, 20/11/2013 11:27

O projeto Simulação Computacional de Multidões: Prevendo e Evitando Desastres, da Faculdade de Informática da PUCRS, foi o vencedor do Prêmio Santander Ciência e Inovação, na categoria Tecnologia da Informação e Comunicação.

Equipe CrowdSim: Luiz Cunha, Soraia Musse, Vinicius Cassol e Anderson da Silva. Foto: divulgação

- **Software gaúcho monitora multidões**
- **Tecnologia ajuda, mas não é a solução**
- **PUC-RS terá treinamentos Apple**

A iniciativa premiada, coordenada pela professora Soraia Musse, criou o CrowdSim, um software capaz de simular a evacuação em locais com grande aglomeração de pessoas, como estádios de futebol, shows, espetáculos, escolas ou prédios residenciais e comerciais.

A ferramenta simula os movimentos de pedestres, cujos resultados podem ser usados para a escolha da localização de câmeras de segurança, saídas de emergência, redimensionamento de corredores, portas e áreas de trânsito.

“A grande utilidade do CrowdSim é a prevenção de problemas e exploração de diversas situações sem colocar as pessoas em uma situação falsa em que o comportamento caótico é interferido por ter consciência de que se trata de uma simulação”, afirmou a professora em entrevista ao Baguete.

Inicialmente, o software foi testado no Estádio Olímpico João Havelange, o Engenhão, no Rio de Janeiro. Para isso, foram levantados dados da estrutura física, capacidade de lotação e ocupação durante os jogos para configurar a ferramenta.

Além disso, a boate Santa Mônica, em Porto Alegre, também foi utilizada para os testes do simulador.

Também participaram do desenvolvimento do projeto os alunos de doutorado Vinicius Cassol e Amyr Borges; os alunos de graduação Alexandre Carvalho, Cristiano Martins, Estevão Testa e Rodrigo Ramos; os ex-alunos de mestrado Marcelo Paravisi e Rafael Rodrigues; e os funcionários da Universidade Luiz Cunha e Anderson Silva.

C. PUBLICATIONS

Analyzing Egress Accuracy through the Study of Virtual and Real Crowds

Vinícius Cassol, *Jovani Oliveira, Soraia Raupp Musse, and Norman Badler*
Workshop on Virtual Humans and Crowds for Immersive Environments (VHCIE) on IEEEVR 2016: Greenville, SC, USA .
Workshop Paper

An approach to validate Crowd Simulation Software: a case study on CrowdSim

Vinícius Cassol, *Jovani Oliveira, Adriana Braun, Amyr Borges Fortes Neto and Soraia Musse*
Proceedings of Fourteenth Brazilian Symposium on Games and Digital Entertainment (SBGames 2015): Teresina, Brazil.
Available in: `ColocarLinkDaIEEE.com`
Conference Paper

An approach to Simulate Heterogeneous Behaviors in Virtual Crowds under Alcohol

Vinícius Cassol, *Cliceres Mack Dal Bianco, Alexandre Carvalho, Maristela Monteiro, and Soraia Musse*
Proceedings of Fifteenth International Conference on Intelligent Virtual Agents (IVA 2015): Delft, The Netherlands.
DOI: `10.1007/978-3-319-21996-7_13`
Conference Poster

Evaluating perceived trust from procedurally animated gaze

Aline Normoyle, Jeremy B. Badler, Teresa Fan, Norman I. Badler, ***Vinicius J. Cassol****, and Soraia R. Musse.*
Proceedings of Motion on Games (MIG '13). ACM, New York, NY, USA, 2013.
DOI: `10.1145/2522628.2522630`
Conference Paper

Simulando Multidões no Parque Tecnológico da PUCRS

Estevão Testa, Cristiano Martins, Rodrigo Ramos, Alexandre Carvalho, ***Vinícus Cassol****, Anderson Silva, Luiz Cunha and Soraia Musse.*
Workshop on Work in Progress - SIBGRAPI. Arequipa, Peru, 2013.
Available in: `http://www.ucsp.edu.pe/sibgrapi2013/eproceedings/wip/115914.pdf`
Conference Paper

CrowdVis: A Framework for Real Time Crowd Visualization

Henry Braun, Fernando Marson, Rafael Hocevar, ***Vinícius Cassol*** *and Soraia Musse*
Proceedings of ACM SAC 2013:Porto, Portugal.
DOI: `10.1145/2480362.2480551`
Conference Paper

A Procedural Approach to Simulate Virtual Agents Behaviours in Indoor Environments

Laura Flach, ***Vinícius Cassol****, Fernando Marson and Soraia Musse.* Proceedings of SBGames 2013: São Paulo, Brazil.
Available in: `http://www.sbgames.org/sbgames2013/proceedings/comp/14-full-paper.pdf`
Conference Paper

A Procedural Approach to Simulate Virtual Agents Behaviours in Indoor Environments

Laura Flach, ***Vinícius Cassol****, Fernando Marson and Soraia Musse.* Proceedings of IVA 2013:Edinburgh, United Kingdom (pg. 448-449)
Conference Poster

CrowdSim: Uma ferramenta desenvolvida para Simulação de Multidões

Vinícius Cassol, *Rafael Rodrigues, Luiz Cunha, Anderson Silva and Soraia Musse*
Workshop de Simulação do SBGames - SBGames 2012: Brasília, Brazil.
Available in: `http://sbgames.org/sbgames2012/proceedings/papers/simulacao/W_1.pdf`
Conference Paper

Applications: Case Studies

Book Chapter Contribution: Crowd Simulation. 2ed.London: Springer-Verlag, 2012. From Daniel Thalmann and Soraia Musse

Towards a quantitative approach for comparing crowds

Soraia Musse, ***Vinícius Cassol*** *and Cláudio Jung*

Computer Animation and Virtual Worlds: Chichester, UK, 2012.

DOI: `10.1002/cav.1423`

Conference Paper

From their Environment to their Behavior: A Procedural Approach to Model Groups of Virtual Agents

Rafael Hocevar, Henry Braun, Fernando Marson, ***Vinicius Cassol****, Rafael Bidarra, Soraia Musse*

Proceedings of IVA 2012: Santa Cruz, California ,USA.

DOI: `10.1007/978-3-642-33197-8_38`

Conference Paper

D. SOFTWARE REGISTRATION

CrowdSim is already registered on National Institute of Intellectual Property (INPI - Brazil). The register was published on *Revista da Propriedade Industrial (RPI) n^o. 2306* in March 17th, 2014 and is valid until December 20th, 2023.

Criador: ELAINE CRISTINA CAMBUI BARBOSA; JOSE GARCIA VIVAS MIRANDA; RODRIGO NOGUEIRA DE VASCONCELOS
Linguagem: C++; QT-4
Campo de Aplicação: EL-01
Tipo de Programa: FA-01
Data da Criação: 13/11/2012
Regime de Guarda: SEM SIGILO ATÉ 28/12/2022
Procurador: Não informado ou inexistente

Processo: 14229-2 **090**
Título: CTRL-E
Titular: JENINFER GREBEL FUENTES CELIS REIN
Criador: JENINFER GREBEL FUENTES CELIS REIN
Linguagem: AJAX; JAVASCRIPT; PHP
Campo de Aplicação: AD-05; AD-08; AD-09; AD-10; SV-03
Tipo de Programa: AP-01; AP-02; AP-03; GI-01; GI-04
Data da Criação: 10/01/2007
Regime de Guarda: SIGILO ATÉ 21/12/2022
Procurador: Não informado ou inexistente

Processo: 14230-1 **090**
Título: ARKIVUS FINANCE
Titular: ARKIVUS SOLUÇÕES TECNOLÓGICAS LTDA; FLAMEX-AGENDAMENTO DE CONTRATOS LTDA
Criador: JONATHAN MICHEL PUZZI MOSER
Linguagem: HTML5; JAVASCRIPT; VB.NET
Campo de Aplicação: FN-03; FN-05; IF-02
Tipo de Programa: AT-03; FA-01; GI-01
Data da Criação: 30/11/2012
Regime de Guarda: Sem sigilo
Procurador: Não informado ou inexistente

Processo: 14231-3 **090**
Título: CRD - CARREIRA,RENUMERAÇÃO E DESEMPENHO:METODOLOGIA MATRICIAL
Titular: SALARIOS WEB TECNOLOGIA DA INFORMACAO
Criador: CARLOS ALEXANDRE DA SILVA; JOSE CARLOS SILVA DAMASCENO
Linguagem: ADOBE FLEX; PHP
Campo de Aplicação: AD-02; AD-07; TB-02
Tipo de Programa: AP-01; DS-07
Data da Criação: 02/01/2010
Regime de Guarda: Sem sigilo
Procurador: Não informado ou inexistente

Processo: 14234-2 **090**
Título: SDSIC- SISTEMA DE DEMANDAS DO SERVIÇO DE INFORMAÇÕES AO CIDADÃO
Titular: MINISTÉRIO DO PLANEJAMENTO, ORÇAMENTO E GESTÃO
Criador: MARCELO LINHARES CASTRO
Linguagem: JAVASCRIPT; PHP
Campo de Aplicação: IF-07; IF-10
Tipo de Programa: DS-02
Data da Criação: 02/04/2012
Regime de Guarda: Sem sigilo
Procurador: FERNANDO ANTÔNIO BRAGA DE SIQUEIRA JÚNIOR

Processo: BR 50 2013 001515-8 **090**
Título: EIS- MAPPER - ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY MAPPER
Titular: IVAN NAPOLEÃO BASTOS; MARCO ANDRÉ ABUD KAPPEL; RICARDO FABBRI; ROBERTO PINHEIRO DOMINGUES
Criador: IVAN NAPOLEÃO BASTOS; MARCO ANDRÉ ABUD KAPPEL; RICARDO FABBRI; ROBERTO PINHEIRO DOMINGUES
Linguagem: SCILAB 5.4.1
Campo de Aplicação: FQ-12; IN-02; IN-03; IN-05
Tipo de Programa: DS-04; IT-01; TC-01
Data da Criação: 01/06/2013
Regime de Guarda: Sem sigilo
Procurador: Não informado ou inexistente
RETIFICAÇÃO DE PARTE DA EXIGÊNCIA POR TER SIDO INDEVIDA (SOLICITAÇÃO DO DOCUMENTO DE CESSÃO DE DIREITOS).

Processo: BR 50 2014 000001-3 **090**
Título: DERIVATIVES SIMULATOR
Titular: PAULO LAMOSA BERGER
Criador: PAULO LAMOSA BERGER
Linguagem: ASP.NET; VISUAL STUDIO; XHTML
Campo de Aplicação: EC-06; EC-13; FN-02; FN-03; FN-05
Tipo de Programa: AP-01; DS-04; ET-04; SM-01
Data da Criação: 01/01/2003
Regime de Guarda: SIGILO ATÉ 02/01/2024
Procurador: Não informado ou inexistente

Processo: BR 50 2014 000523-6 **090**
Título: REFERENTIAL-GRAPH METATEXT
Titular: ITAMAR SOARES VEIGA
Criador: DANIEL MÜLLER DA SILVA ; ITAMAR SOARES VEIGA
Linguagem: JAVASCRIPT; PHP; XHTML/CSS
Campo de Aplicação: CO-03; CO-04; IF-02; IF-05; MT-06
Tipo de Programa: FA-02; FA-04; IA-01; IA-03; TC-01
Data da Criação: 20/05/2013
Regime de Guarda: SIGILO ATÉ 20/05/2024
Procurador: Não informado ou inexistente

Processo: BR 51 2013 000990-1 **090**
Título: SWH-FD - STACK WIRELESSHART - FIELDDEVICE
Titular: PETRÓLEO BRASILEIRO S./A. - PETROBRAS; UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
Criador: CARLOS EDUARDO PEREIRA; IVAN MÜLLER; JOÃO CESAR NETTO
Linguagem: C
Campo de Aplicação: IN-05
Tipo de Programa: SO-04
Data da Criação: 01/02/2013
Regime de Guarda: SIGILO ATÉ 10/09/2023
Procurador: Não informado ou inexistente
EXIGÊNCIA DEVIDAMENTE CUMPRIDA PELA PETIÇÃO (RJ)020140028359 DE 10/09/2014

Processo: BR 51 2013 001028-4 **090**
Título: SISTEMA INTEGRADO GESTÃO ADMINISTRATIVA
Titular: RODO REAL CONSULTORIA S/A
Criador: MARCELO LUIZ DE FARIA
Linguagem: C-SHARP
Campo de Aplicação: AD-02; AD-04; AD-05; PL-01; PL-02
Tipo de Programa: AP-01; AP-02; AP-03; AP-04
Data da Criação: 01/08/2013
Regime de Guarda: SIGILO ATÉ 25/03/2014
Procurador: Não informado ou inexistente
EXIGÊNCIA CUMPRIDA.
PETIÇÃO/PROTOCOLO 014140001777/MG

Processo: BR 51 2013 001230-9 **090**
Título: PIA² - PLATAFORMA DE INOVAÇÃO ABERTA VERSÃO ACADEMIA
Titular: ASSOCIAÇÃO PARANAENSE DE CULTURA - APC
Criador: EDUARDO OLIVEIRA AGUSTINHO; JOSÉ GERALDO LOPES DE NORONHA FILHO; LUIZ MÁRCIO SPINOSA; MARCELO MIRA DA PAZ; MAURO KATSUSHI NAGASHIMA; NILSON DA SILVA REIS
Linguagem: ASP.NET 2.0
Campo de Aplicação: AD-05; CO-02; IF-01; IF-07; IN-02
Tipo de Programa: AP-05; GI-01; GI-02; GI-04; TC-01
Data da Criação: 01/10/2008
Regime de Guarda: SIGILO ATÉ 08/11/2023
Procurador: VALOR PROPRIEDADE INTELECTUAL S/S LTDA
EXIGÊNCIA CUMPRIDA.
PETIÇÃO/PROTOCOLO 015140001958/PR

Processo: BR 51 2013 001277-5 **090**
Título: SIGMAN - SISTEMA DE GESTÃO EM MANUTENÇÃO
Titular: SANDRA PEREIRA DE MATTOS - ME
Criador: EDUARDO CAMARA DE MATTOS
Linguagem: HTML; JAVASCRIPT; PHP
Campo de Aplicação: AD-01; AD-05; AD-08; AD-09
Tipo de Programa: DS-04; FA-01; GI-01; SO-07
Data da Criação: 05/11/2013
Regime de Guarda: SIGILO ATÉ 21/11/2023
Procurador: Não informado ou inexistente
EXIGÊNCIA CUMPRIDA.
PETIÇÃO/PROTOCOLO 016140002271/RS.

Processo: BR 51 2013 001378-0 **090**
Título: JOGO DE INOVAÇÃO
Titular: UNIVERSIDADE DO ESTADO DO RIO DE JANEIRO
Criador: ADRIANO FRANCISCO DA SILVA; BRANCA REGINA CANTISANO DOS SANTOS E SILVA; DIOGO LOBATO DIUANA; MARCELO ANDRADE DA SILVA; MARCIA TABORDA CORRÊA DE OLIVEIRA; MARIZA COSTA ALMEIDA; MICHELE PEREIRA FIGUEIREDO; RAPHAEL MADUREIRA DE OLIVEIRA ; RICARDO MIYASHITA
Linguagem: HTML5; JAVA
Campo de Aplicação: ED-01; ED-04; IN-02
Tipo de Programa: SM-02
Data da Criação: 04/11/2013
Regime de Guarda: SIGILO ATÉ 18/12/2023
Procurador: JOSÉ CARLOS VAZ E DIAS

Processo: BR 51 2013 001388-7 **090**
Título: CROWD SIM - SOFTWARE PARA SIMULAÇÃO E ANÁLISE DO COMPORTAMENTO DE MULT
Titular: UNIÃO BRASILEIRA DE EDUCAÇÃO E ASSISTÊNCIA - MANTENEDORA DA PUCRS
Criador: SORAIA RAUPP MUSSE; VINÍCIUS JURINIC CASSOL
Linguagem: C++; OPENGL
Campo de Aplicação: TP-01; TP-04; UB-01
Tipo de Programa: SM-01
Data da Criação: 10/08/2012
Regime de Guarda: SIGILO ATÉ 20/12/2023
Procurador: REMER VILLAÇA & NOGUEIRA ASSES.E CONS.DE PROPRIEDADE INTELECTUAL S/S LTDA.
EXIGÊNCIA CUMPRIDA.
PETIÇÃO/PROTOCOLO 016140002439/RS.

Processo: BR 51 2013 001434-4 **090**
Título: SISMOTEL - SISTEMA DE GESTÃO E AUTOMAÇÃO DE MOTÉIS
Titular: MICROTECS INFORMÁTICA LTDA
Criador: RÔMULO RODRIGUES SIMÕES
Linguagem: DELPHI
Campo de Aplicação: AD-05; FN-02; IF-01; IF-10; SV-04
Tipo de Programa: AP-01; AT-01; CD-04
Data da Criação: 27/11/2002
Regime de Guarda: SIGILO ATÉ 27/12/2023
Procurador: Não informado ou inexistente
EXIGÊNCIA DEVIDAMENTE CUMPRIDA PELA PETIÇÃO SEM PROTOCOLO COM GRU 0000271408773580 COM PAGAMENTO CONCILIADO NO PAG

Processo: BR 51 2014 000033-8 **090**
Título: MODMATSTAT
Titular: UNIVERSIDADE ESTADUAL PAULISTA JÚLIO DE MESQUITA FILHO - UNESP
Criador: AUGUSTO BATAGIN NETO; FRANCISCO CARLOS LAVARDA
Linguagem: BASH SCRIPT; FORTRAN 77; FORTRAN 90
Campo de Aplicação: FQ-08; FQ-13; FQ-14; MT-06; SD-10
Tipo de Programa: SM-01; TC-01; TC-03
Data da Criação: 01/10/2006
Regime de Guarda: SIGILO ATÉ 20/01/2024
Procurador: FABÍOLA DE MORAES SPIANDORELLO
EXIGÊNCIA CUMPRIDA.
PETIÇÃO/PROTOCOLO 018140018156/SP.

Processo: BR 51 2014 000043-5 **090**
Título: SINAPSE SISTEMA INTEGRADO DE PESQUISA E ANÁLISE DE DADOS
Titular: TRIBUNAL DE CONTAS DA UNIÃO
Criador: JOÃO BATISTA RODRIGUES FONSECA; MARCO ANTÔNIO MAGALHÃES CAVALCANTI
Linguagem: ORACLE APEX
Campo de Aplicação: AD-04
Tipo de Programa: AP-03; AP-04
Data da Criação: 01/06/2013
Regime de Guarda: SIGILO ATÉ 23/01/2024
Procurador: PAULO ANDRÉ MATTOS DE CARVALHO
EXIGÊNCIA CUMPRIDA.
PETIÇÃO/PROTOCOLO 012140000298/DF.

Processo: BR 51 2014 000075-3 **090**
Título: GIN - GESTÃO DA INFORMAÇÃO
Titular: GEOHUB PROCESSAMENTO E GERÊNCIA DE DADOS LTDA
Criador: AUGUSTO MELLO RANGEL; DANIELLE ROCHA; FELIPE DOMINGUES ROCHA; JOÃO CARLOS CORRÊA; RICARDO DA SILVA COELHO
Linguagem: .NETC#; ASP.NET C#; JAVASCRIPT
Campo de Aplicação: AD-05; IF-02; IF-10
Tipo de Programa: GI-02; GI-06; GI-07; SO-07
Data da Criação: 01/07/2011