MULTISCALE MODELLING AND SIMULATION OF FIRE EMERGENCY EVACUATION USING ADVANCED TECHNOLOGIES

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MULTISCALE MODELLING AND SIMULATION OF FIRE EMERGENCY EVACUATION USING ADVANCED TECHNOLOGIES

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Fire is one of the most severe hazards to which built infrastructure and human lives may be subjected. In the last few years, the development of modern technologies such as numerical simulations, virtual and augmented reality, represent a proper alternative to the actual fire drill. This work introduces a multiscale methodology for the simulation of fire emergency response through a virtual reality-based system by integrating a computational fluid dynamics (CDF) computer software into a virtual reality model.

The proposed methodology offers an accurate visualization of the fire propagation and its progressive extension. This represents an important aspect of the work, since to date, fire emergency scenarios have been simulated by using internal libraries and features of virtual reality software (e.g., particle system in Unity software).

To demonstrate the applicability of the proposed methodology, two case studies at different scales are proposed: a building school in the hinterland of Milan and the city of Bolinas in California.

Results show that the methodology can be used for reproducing fire emergency scenarios realistically and can help decision-makers to determine the fire rescue and fire protection planning. Moreover, the proposed virtual reality-based system can be used by firefighters to perform repetitive emergency evacuation and rescue training and improve their abilities in a safe environment.

CH. 1

INTRODUCTION

Wilson, J., Fire burning inside a large oak tree on a ranch in Vacaville. (2020) *The New York Times*

FIRE AND WILDFIRES HAZARD

Fire is one of the most severe hazards to which built infrastructure and human lives may be subjected. Fire frequently results in economic losses and human death due to the toxic gases released by smoke as well as disastrous scenarios caused by wildfire. In recent years, Fire Safety Engineering (FSE) has changed the way designers think, questioning the validity of current regulations.

Fire Safety Engineering takes care of the application of rules and judgements based on the scientific evaluation of the phenomenon of combustion, the effects of fire and human behavior aimed at the protection of human life, and the environment. The quantification of risks and the analytical assessment of the optimal prevention measures are necessary to limit the consequences of fire, to face and solve many fire prevention problems going beyond the traditional prescriptive methods provided by the technical rules.

The development of more accurate calculation models has led to more realistic simulations of fire emergency scenarios. That is, such simulations allow calculating exactly the time people have to escape, or the time the structures can resist. In the traditional approach, this calculation is replaced by conventional evaluations, which are adapted to entire classes of buildings without any particular distinction of their actual content.

The performance methodology of Fire Safety Engineering is based on the identification of protection measures carried out by identifying fire scenarios specifically designed for this purpose. And, unlike prescriptive standards, which are mainly based on an empirical approach, Fire Safety Engineering is based on a scientific-predictive perspective.

The prescriptive approach appears rigorous and the designer is driven in his work by standard prescriptions set in advance. The designer is required to follow well-specified procedures and methods of calculation and detailed construction aspects. If in the past this approach could be efficient from the design point of view, in recent years there has been the need to use a tool that allows greater flexibility, thanks to the technological progress in these areas.

The realization of structures more distant from the standard ones of the past, characterized by complex geometries and spaces of particular architectural and constructive relevance, has made almost completely unusable the old regulations based on performance approaches. Indeed, they do not adapt to specific situations of a given project as they are not designed for them. The performance methodology defines the performance that the structure must be able to achieve. It differs from the previous method since it focuses on the objective for which the structure is built, rather than how it must be built.

The performance methodology allows a quantitative evaluation of the level of fire safety in relation to the performance thresholds and fire scenarios. Opportune models of calculation able to foresee the effects of a determined event and the measures to adopt would be required to implement the performance analysis.

The strength of a performance approach stands in the high flexibility and consequent adaptability to complex situations up to saving from an economic point of view. The main economic advantage is that, considering the performance of each building, it is easier to plan specific security measures, optimizing costs of management, materials and adaption works.

In the prescriptive approach instead, the designer should apply several security measures based on the category of building, without considering the effective utility of them. This brings to overestimate the security increasing the costs. The prescriptive legislation makes its application to all buildings very complicated, because of its inflexibility. For instance, in school buildings the fire safety requirements are often overlooked despite several firefighters' interventions are required in school buildings every year.

In the latest data provided by the School Building Register (MIUR), it appears that schools with fire prevention certifications are only 9,824 out of more than 40,000 buildings, while the annual statistics of firefighters report an average of more than 500 interventions per year in schools due to fires or explosions (see Figure 1).

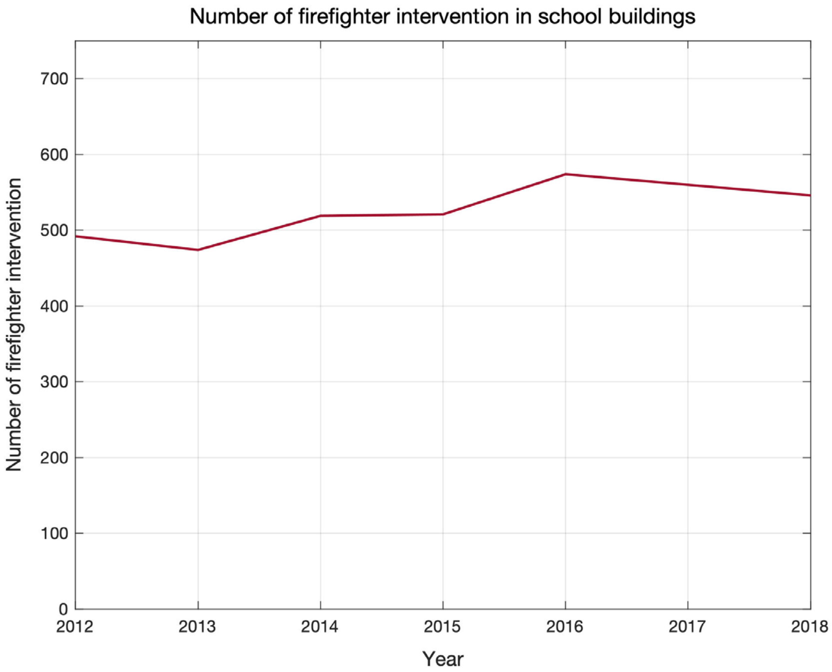


Figure 1. Firefighter intervention in school buildings due to fire and explosion in Italy. The average of intervention in school is from 500 to 600 each year. This is an indicator that it is a protentional and real danger and only one school out of four have the fire prevention certificate.

Over the years, there have been a series of regulations in the field of safety and fire protection. The last Code was introduced in 2015 (D.M 2015), while the specific documentation concerning school buildings was introduced in 2017 (D.M 2017). The new decrees of technical standards of fire prevention in different types of activities (schools, accommodation facilities, offices, commercial activities) are proposed as an alternative to the specific technical standards of fire prevention.

For the purposes of proper fire safety design, the most realistic possible reproduction and visualization of a fire is of great importance when it comes to emergency and risk planning. The development of increasingly advanced and accurate simulation software has made possible the performance approach to design assessments of actual fire and smoke propagation scenarios. The ability to calculate and predict the spread of fires helps to prevent and investigate suitable solutions to minimize damage both in case of fire and wildfires.

Different calculation models for simulate fire and wildfire scenarios have been developed in the last years. One of the main software used in fire and structure simulation is Fire Dynamic Simulator (FDS), a software developed by National Institute of Standards and Technology (NIST) of computational fluid dynamics (CFD) optimized for fire and smoke simulation (McGrattan et al. 2013).

Wildfires are simulated by using FarSite, which is a software widely used by the United States Forest Service and National Park Service. In this context, evacuation planning becomes a key aspect to ensure the protection of human lives. The correct and quick evacuation of people from burning buildings is very important for the saving of lives. However, it is difficult to train occupants for evacuation in a real environment since it is dangerous and expensive. Several models simulating the dynamics of the crowd can be found in the literature (e.g., fluid dynamic, Agent Base Model, cellular automata model, etc.).

With the development of Virtual Reality (VR), the application of this technology has become common in the field of Fire Safety Engineering. With Virtual Reality applied to fire emergency evacuation management, it is possible to reproduce a fire emergency scenario without the disadvantages of high cost and danger, evaluate the human behavior during a virtual fire scene, and simulate emergency evacuation process.

Many attempts have been made to develop training for firefighters or to carry out analyses on human behavior in case of emergency. However, the realization of an overall scenario that brings together different simulations in a virtual reality model is still challenging.

The simulation of real fire and smoke conditions allows making considerations and designing deductions for the most effective planning of escape routes and emergency plans. However, the interaction between numerical results from computational fluid dynamics software and virtual reality model is still missing.

To date, simulations of fire scenario have been reproduced by using simplified methods such as particle systems in Unity 3D software, cellular automata, and assets. For instance, the operating principle of the particle system in Unity 3D is the redrawing of one or two materials to create a chaotic effect This method for smoke simulation shows several weaknesses.

That is, the particles used are colliders inside the software that collide against the walls reproducing the smoke effect. The collision makes the propagation of smoke in the smaller apertures complicated (if the size of the collider is greater than an aperture then the smoke will not propagate). It is also difficult to reproduce the shape of the smoke expansion and its timing, which is essential to recreate the conditions of visibility during the fire.

Therefore, the primary goal of this work is to develop multiscale simulations by integrating the results of a computational fluid dynamics software into a virtual model.

The contribution of this thesis is summarized as follows:

1. Developing a methodology to simulate a fire emergency scenario by combining different inputs.
2. Developing a virtual reality model to integrate outputs from different software.
3. Implementing the virtual reality model as a tool to experience emergency scenario in first person.

4. Presenting two multiscale scenarios (i.e., building scale and urban scale scenario) to demonstrate the applicability of the proposed methodology.

The proposed methodology is targeted as support tool to reproduce fire emergency scenarios realistically and help decision-makers determining the fire rescue and fire protection planning. Moreover, the proposed virtual reality-based system can be used by firefighters to perform repetitive emergency evacuation and rescue training aiming at improving their abilities in a safe environment.

The remainder of the thesis is organized as follows: Chapter 1 is dedicated to reviewing the basic concepts of fire and wildfire hazard and the state of knowledge about existing methodologies in Fire Safety Engineering. Chapter 2 illustrates the workflow framework implemented in this work. The methodology to simulate the fire emergency scenario along with the tools used in this work are described in detail in Chapter 3. The case studies proposed in this work to illustrate the applicability of the methodology are presented in Chapter 4 and Chapter 5, respectively. Finally, Chapter 6 concludes and proposes future work.

LITERATURE REVIEW

Fire Safety Engineering has become increasingly important at a design level. Several publications can be found in the literature focusing on fire and exodus modelling. Gai et al. (2016) described fire simulation and exodus simulation models as tools to bring out critical issues such as smoke propagation timing within a building and delays in evacuation time due to poor visibility that could cause congestion and queues in the evacuation flow.

In fire modelling for Fire Safety Engineering, one of the most used software is Fire Dynamic Simulator. Numerous studies have been carried out on experiments to highlight its validity. Zanut et al. (2017) highlighted the importance of design and fire safety strategies in the management of emergency in building schools. In this work, they proposed a methodological approach to simulate fire emergency scenarios and evacuation processes by using advanced software as Fire Dynamic Simulator (FDS).

Fire Dynamic Simulator has been largely investigated to simulate fire emergency scenarios in different environments such as office buildings (An et al. 2014), industrial hall (Glasa and Steckova 2015), and hotel structures (Shen et al. 2008). Despite the large use of Fire Dynamic Simulator to easily reproduce a fire emergency scenario, the integration of complex geometries within the software is still challenging.

Over the years, many studies have tried to optimize the integration process by using BIM models, that have become fundamental in design. Dimyadi et al. (2007) analyzed methodologies to connect BIM models and the modeling of geometries in the Fire Dynamic Simulator (FDS) code, developing an appropriate tool to overcome this problem.

In the last years advanced and sophisticated technologies, such as Virtual Reality (VR), have been investigated in Fire Safety Engineering.

Kinateder et al. (2014) outlined the importance of Virtual Reality as laboratory tool in studying human behavior in fire emergency scenarios and in improving safety performance through SWOT analysis. The SWOT analysis is a strategical approach where Strengths, Weaknesses, Opportunities, and Threats of an idea or a decision are defined. In this way, it is easier to understand if the positive aspects are more than the negative ones. Table 1summarizes the SWOT analysis parameters.

Table 1 Summary of a SWOT analysis for Virtual Reality (VR) in fire evacuation research (from (Kinateder et al. 2014)

Strengths	Weaknesses	Opportunities	Threats
• Internal validity • Replication • Ecological validity • External validity • Safety for participants • Real-time feedback • Multi-modal simulations • Precise measurement • Psychophysiological monitoring • Low costs • Repeated measurements • Flexibility • Control of confounding variables • Independent of imagination abilities/willingness of participants • Participant recruitment	• Need for confirmation/validation • Non-intuitive interaction methods • Inter-individual differences in ease of interaction with VR • Technical limitations • Technology-induced side effects • Efforts	• Intuitive and natural navigation • Graphical developments • Multi-modal simulation and feedback • Usability for researchers • Exchange of 3D-scenes or experiments	• Failure to show ecological validity • Ethical challenges • Side-effects due to interaction with other medical conditions • Misleading expectations • Technical faults

Lee and Wong (2014) explained that the use of virtual reality influences in a positive way the cognitive domain of learning. Guo et al. (2012) realized a virtual reality model for safety training in construction plant operation allowing trainees to make some construction plant tasks without any danger, to improve the knowledge of the operating process, and to identify safety problems. Many studies have approached the validation of the actual benefits of Virtual Reality applied to Fire Safety Engineering.

For instance, Lovreglio et al. (2020) proposed a comparative study on the effects of teaching some firefighting maneuvers through simple videos or a virtual reality experience. After four weeks, it was verified how those who experienced virtual reality were able to remember much better what they had learned while the group that had seen the video showed a significant drop in the ability to replicate the operations.

Similarly, the efficacy of virtual reality training compared to the traditional training approach was investigated by Chittaro (2015); Chittaro et al. (2018). Also, Backlund et al. (2009) showed that participants in a study on firefighter training found the virtual reality training more educative, easier, and enjoyable than the traditional one. Besides, Poole (2012) claimed that only 40% of people can use correctly a fire extinguisher and some people get injured trying to use it due to the lack of knowledge about its functionality.

The lack of personal knowledge on fire safety is identified as one of the main factors for fire-related injuries and deaths (De Gloria et al. 2014). Wang et al. (2014) proposed a study to verify the validity of the use of virtual reality in Fire Safety Engineering. In this paper a virtual environment in a fire situation was created to experience human behavior in a state of anxiety. After a comparison with data coming from a real situation of fire, it comes verified like the results were similar, indicating virtual reality as an effective instrument to study the human behavior under stressful conditions.

Thus, virtual reality serious game shows several advantages in the training process and improving personal skills in fire emergency situation and it is a really efficient method to collect information saving time and money (Kobes et al. 2010).

Several serious games have been developed with the aim to test and improve fire safety skills by integrating the process of evacuating from the virtual environment (Burigat and Chittaro 2016; Cha et al. 2012; Chittaro and Ranon 2009; Kinateder et al. 2014; Rüppel and Schatz 2011; Smith and Trenholme 2009). Moreover, several researchers have developed emergency simulations in a virtual environment, when movements and interaction with the surrounding environment are allowed. Argasiński et al. (2018) developed a training program for firefighters through a virtual reality model.

The BIM implementation in virtual reality aiming at reproducing a fire emergency evacuation scenario was investigated by (Wang et al. 2014). Feng and Xiao (2018) developed a platform to execute fire drills in virtual reality using Kinect technology. Other applications regard the use of virtual reality to study the human behavior in emergency conditions (Feng et al. 2015; Oliva et al. 2019) and evaluate the performance of a building in case of an emergency evacuation (Ren et al. 2006).

Despite the high number of applications in a virtual environment, few simulations implement Fire Dynamic Simulator to recreate a fire scenario within a virtual model. A solution regarding the importing of smoke from Fire Dynamic Simulator (FDS) directly into a Unity 3D model was proposed by St. Julien and Shaw (2003); Xu et al. (2014). The proposed approach is based on the concept of a voxel grid. However, this approach is complex due to the calibration of the voxel grid on which the smoke reconstruction is based. Moreover, the simulation developed in (Xu et al. 2014) focuses on the smoke and effects of smoke toxicity based on a Fractional Effective Dose (FED) model , which is a model that categorizes the toxicity of smoke according to an exposure of 30 minutes. That makes the methodology suitable for a specific study of the effects of smoking, but hardly applicable in simulations with different purposes.

CH. 2
SYSTEM ARCHITECTURE

Bolinas photo courtesy of Peter Hubbard

SYSTEM ARCHITECTURE

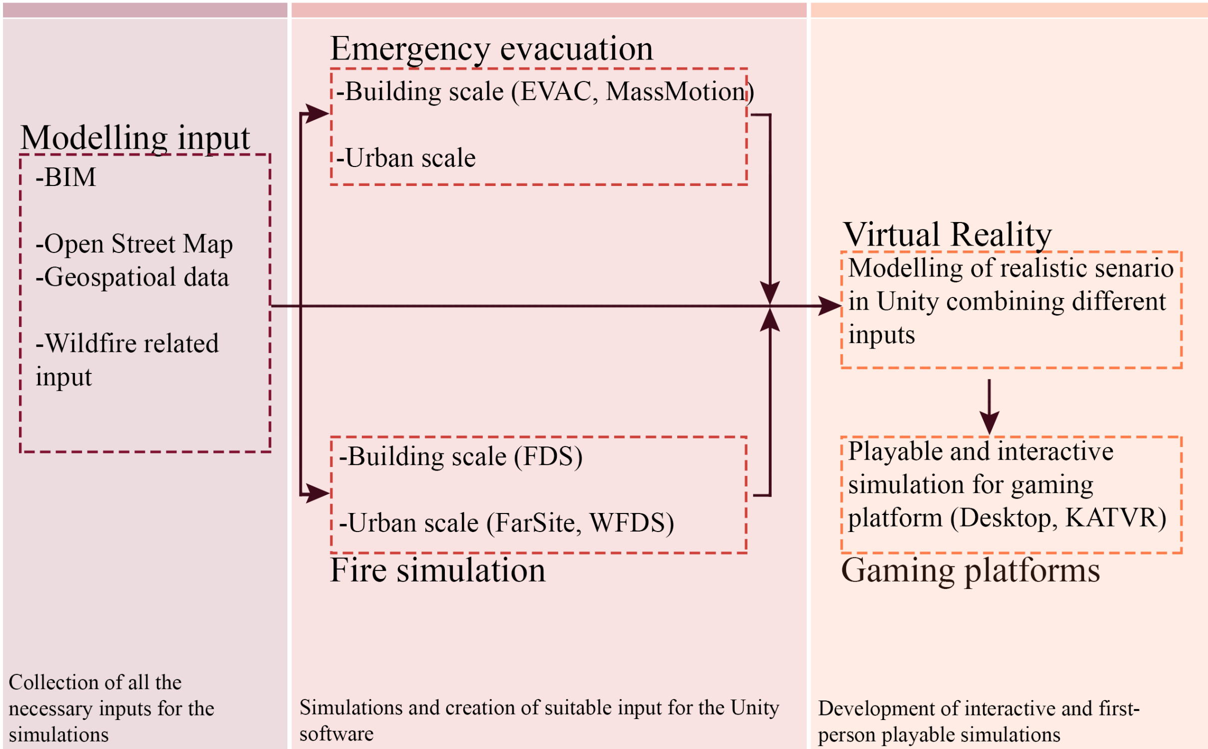


Figure 2. Flowchart of the proposed methodology for elaborate complex and interdisciplinary virtual reality simulation. The proposed approach has been applied on both the case study, building and urban.

As it is shown in Figure 2, the flowchart summarizes all the main steps of the multiscale methodology presented in this thesis.

Modelling input

The first step of the methodology is the collection of all the input necessary for the simulation. It is important that most of them, when possible, have common origins and try to do not use many different data.

One of the main resources for the school building is the BIM model.

Building Information Modeling is a type of three-dimensional modelling where information on structure and material can be collected and analyzed.

The use of this type of model is largely compatible with most of the software dedicated to Fire Safety Engineering.

In this case the same model has been used for simulating fire, evacuation system, and building the geometry in Unity 3D software.

Other data are available for free on online databases such as Open Street Map for road network or Landfire for wildfire related input.

Emergency evacuation

The second step of the proposed methodology is modelling two main aspects of the simulations: evacuation system and fire. On a building scale the emergency evacuation can be simulated with the use of specific software for crowd like MassMotion or Evac.

Agent based model is implemented to characterize each agent with different features of size or speed. On the urban scale, instead, the emergency evacuation is modeled as a traffic simulation.

Fire simulation

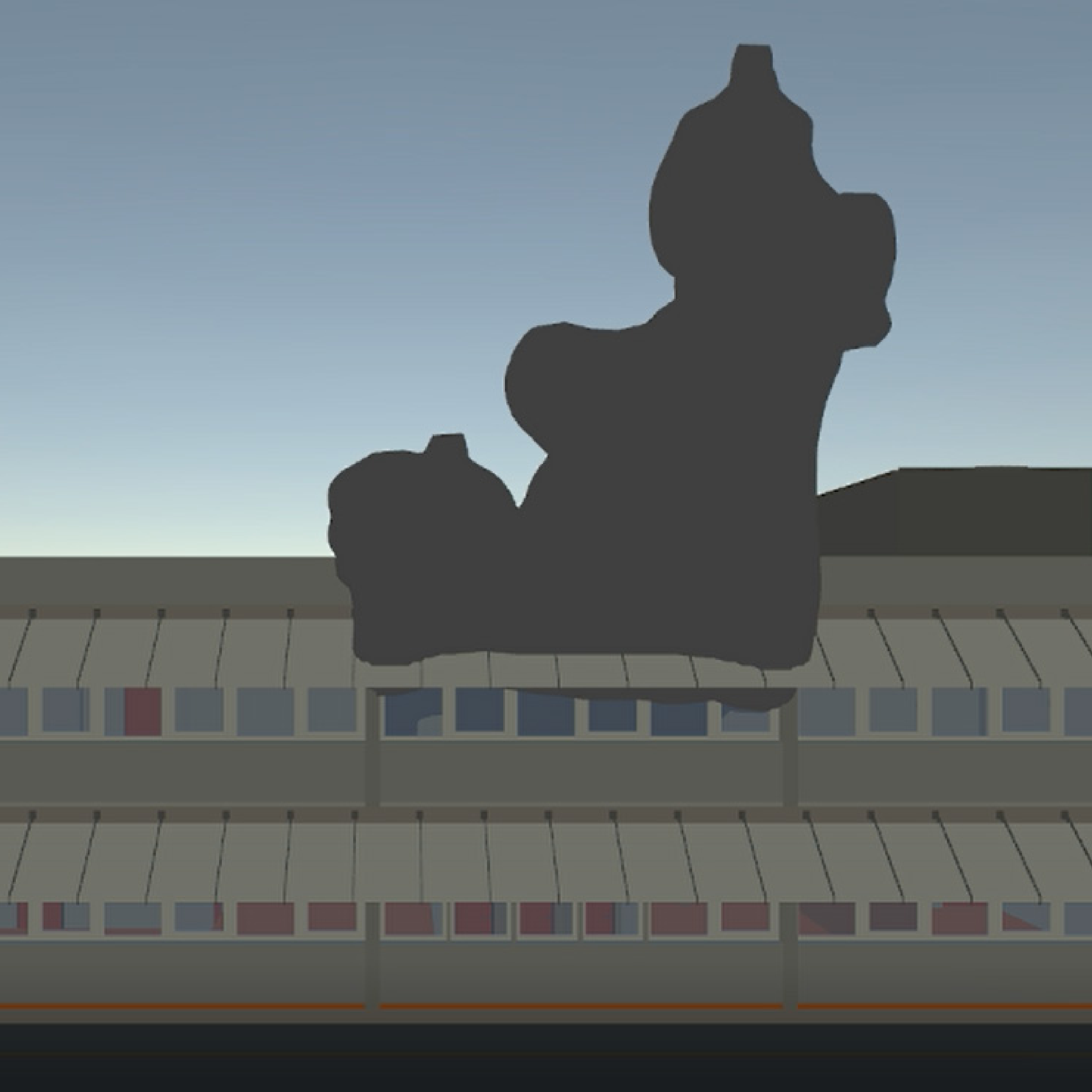
The fire simulation is one of the most important aspect in the planning or analyzing escape routes. Different software are available to simulate fire scenario.
They can be physic-based model (Fire Dynamic Simulator, FDS, or wildland-urban interface fire dynamics simulator, WFDS) or based on semi-empirical observations as FarSite.

Virtual Reality

The last step of the methodology is dedicated to virtual reality and to build a realistic scenario combining all the results of previous simulations through Unity3D software. Unity3D is a software for the development of games written in C++ code.
It is a powerful tool and is the more suitable to import and combine different output from simulation that, apparently, cannot communicate between each other.
One of the biggest advantages of Unity3D software is the possibility to model the scenario in virtual reality, giving the possibility to create an immersive scenario for the final simulation.

Gaming platform

Once the simulation has been developed, it is made playable and interactive for gaming platform. There are many different gaming platforms, from less immersive as desktop, to very immersive platforms. One of the latest tools in the field of gaming is the KATVR, a platform that allows a completely immersive experience where also the movement is related to the real body movements and not just with the triggers of the remote.



CH. 3

METHODOLOGY

TO BUILD THE VIRTUAL REALITY MODEL

SIMULATION OF FIRE

The phenomenon of fire is caused by the combustion of substances. Combustion is an exothermic chemical reaction of a combustible substance with a comburent that causes the development of heat, flame, gas, smoke, and light.

It is called combustion any chemical reaction in which fuel, i.e., an oxidizable substance, reacts with a comburent, i.e., an oxidizing substance, releasing energy, usually in the form of heat. Only the simultaneous presence of these three elements gives origin to the phenomenon of fire, and consequently, the absence of at least one of them extinguishes the fire.

Most fires, however, originate directly or indirectly from human factors. The number of fires due to natural causes (lightning or volcanic eruptions) is very low.

The evolution of fire is divided into four characteristic phases: ignition phase, propagation phase, flash over, and fire extinction. The ignition phase is very unstable and can be influenced by material and their level of flammability but also by the geometry of the environment where the fire is.

In the propagation phase there is the production of toxic and corrosive gases and the visibility is reduced. The third phase is the flashover, there is a sharp increase in temperature and an exponential growth in combustion speed and a in gas emissions.

When the fire has finished affecting all the combustible material, there is the phase of decreasing temperatures inside the room due to the progressive decrease in residual heat contribution and heat dissipation.

The combustion reaction origin four products: combustion gases from the chemical reaction of the material with the fire, flames, smoke, and heat.

Smoke is formed by very small solid and liquid particles. Solid particles are unburned substances that are formed when combustion occurs in oxygen deficiency and are dragged by the hot gases produced by the combustion itself.

Normally they are produced in such quantities that they prevent visibility and hinder the activity of rescuers and the exodus of people. The solid particles of smoke that are unburnt and ash make the smoke dark.

Wildfire is a more complex phenomenon since it involves many environmental factors (e.g., vegetation) and even the change of one of them can affect the result.

The weather conditions affect the spread of fire both through wind and moisture. They are constantly evolving and for this reason, they have an especial importance in the development of wildfires.

The evolution of a wildfire can be summarized in four steps. In the initial growth phase, the intensity of the fire front is quite low. The second phase is the transition phase. The intensity of the fire increases and the front assumes greater dimensions. After this phase, the fire reaches its maximum intensity, there is an enormous amount of thermal energy released from the fire front, and there is the presence of spotting and swirling phenomena. This phase is the most devastating consequences. Finally, there is the decay phase. There is the deceleration of the speed of the frontline and a progressive decrease in the intensity of the fire; it can be slow or even sudden and occurs as a result of changed weather conditions, topography, or the characteristics of the plant fuel concerned.

The modelling of fires is the analysis and simulation of the phenomenon of fire propagation through tools of theoretical analysis, physical and numerical models.

The models used in this thesis are Fire Dynamics Simulator (FDS) for fire in structures, instead for wildfire has been used the physics-based model Wildland-Urban Interface Fire Dynamics Simulator (WFDS) and the semi-empirical model FarSite included in the software FlamMap.

Fire Dynamic Simulator (FDS)

Fire Dynamics Simulator (FDS) is one of the main models referred to when talking about fire simulation. It is an open-source software developed by National Institute of Standards and Technologies (NIST) and is part of the models based on computational fluid dynamics (CFD).
The computational dynamic fluid estimates the behavior of fluid flows in turbulent regime, in particular, Fire Dynamics Simulator (FDS) uses this approach to simulate the phenomenon of fire and smoke propagation through the resolution of Navier-Stokes equations optimized for low-speed flows. The Fire Dynamics Simulator (FDS) simulation can be created using a text file that can be written manually or with the help of graphical interfaces such as Pyrosim (Thunderhead Engineering) or with an extension for the free 3D modeling software Blender (BlenderFDS).
The goal of simulating a fire scenario is to understand and analyze the dynamics of a possible fire as well as the analysis of several physical parameters. Simulating the dynamics of fire makes easier to understand the effect that a potential scenario may have on the occupants, evaluate the consequences on the structure, and then make risk analyses to adopt appropriate protection and prevention measures.
It must be considered that it is not possible to perfectly replicate real scenario and it is necessary to understand and calibrate a model for have a representative result of the real place.
The model works with a reference domain divided into cells and their number defines the

resolution of the whole model.

Fire Dynamics Simulator (FDS) can model different phenomena such as heat transport and flame combustion products at low speed, radiative and convective heat exchange between gases and surfaces, flame propagation and fire development, fuel pyrolysis, heat, and smoke detector activations, and water extinguishing activation.

This is done employing the following four computational models: Hydrodynamic model, Combustion model, Transmission by radiation, and Sprinklers and detectors.

The hydrodynamic model is based on the numerical resolution of the Navier-Strokes equations optimized for smoke and heat transport and in the combustion model Fire Dynamic Simulator uses just one chemical reaction for all the burning materials.

The software also allows to calculate the heat transport by radiation by the finite volume method (FVM) for convective transport. It is possible to calculate the action of sprinklers and detectors, water droplets and the fact that they can absorb and spread heat radiation.

The input parameters for a Fire Dynamics Simulator (FDS) simulation are described in a unique text file. There are described information about the numerical grid, environment, geometries, materials, and combustion.

The geometry of the model is mainly characterized by SURF input. In fact, in this name list group, there are all the parameters necessary to define the physical characteristics and behavior of each geometry (OBST, VENT).

There are four types of surfaces that can be used: supply, layered, burner and exhaust.

The supply surface indicates an introduction of air or gases in the model. The exhaust surface works as a supply type surface but in this case, the flows are discharged from the surface. Layered is the surface that describes a material or layers of different materials (a wall for example can be described as one surface with different layer of material inside).

When a layered surface is integrated in the model must specify thickness and physical parameters

of the material. Burner is the surface from which the fire is ignited, the main parameters to characterize it are heat reaction rate per unit area (HRRPUA) and combustion reaction. In literature there are a lot of empirical experiments that define the reaction of different material with their heat release curve.
Using this data, the reaction must be defined individually, specifying the chemical characteristics of the fuel described by the number of atoms of carbon, hydrogen, oxygen, and nitrogen. The output types that can be obtained are numerical (.csv format) or graphical (static, dynamic, two-dimensional, or three-dimensional) that represent the motion of smoke and the flows of the main thermodynamic quantities.
It is important to establish in advance the types of output you want to obtain and specify them to the software because Fire Dynamics Simulator (FDS) can calculate a huge amount of data. By positioning devices, it is possible to obtain the measurements of the values at the selected point. Smokeview is the graphic viewer that allows you to see the results of the simulation.
It is available with Fire Dynamics Simulator (FDS) on the National Institute of Standards and Technologies (NIST) website as it has been designed specifically for this purpose.

Wildland Fire Dynamic Simulator (WFDS)

Wildland-Urban Interface Fire Dynamics Simulator (WFDS) is a physics-based model, extension of the structure fire model Fire Dynamics Simulator (FDS).
The Wildland-urban interface Fire Dynamics Simulator has been developed through a collaborative effort between the United States Forest Service and the National Institute of Standards and Technology (NIST).
In physics-based model simulate combustion is an operation extremely complex and, in the

literature, there are few examples of this kind of model optimized for wildfires. The purpose is to understand, interpret, and predict the behavior of fires, to provide support to the operators of environmental protection, for more effective suppression of fires, their prevention, and control, reducing the risks for operators, population, and territory.

Fire modelling seeks to reproduce the behavior of a forest fire during its propagation, simulating the direction and speed of propagation of the flame front, the mode of propagation, the heat produced, and the height of the flames.

It also tries to estimate the environmental effects of fire by calculating the amount of fuel burned, the mortality of trees or the amount of ash dispersed.

The source code of Wildland-Urban Interface Fire Dynamics Simulator (WFDS) is integrated within Fire Dynamics Simulator (FDS) and the structure of the code is similar with the addition of some dedicated input dedicated to vegetation. This model considers the presence of terrain, vegetation, and the spread of fires through vegetation.

There are two type of fire simulations possible in Wildland-urban interface Fire Dynamics Simulator.

The first one is based on semiempirical component and it is indicated as WFDS-LS, this model is a fire front propagation model like the software FarSite and there are no physical processes simulated. It simulates only the fire perimeter and how it moves across the landscape.

The second option of use of Wildland-urban interface Fire Dynamics Simulator is the Physics-Based Component (WFDS-PB) that simulates the fire as a union of the processes of combustion, the environment, the wind, solid fuel burning, and heat transfer.

To solve the equations for the flow are used computational fluid dynamics (CFD) methods. For representing vegetation there are currently two ways.

The Boundary Fuel Model is used for simulating surface fuels, instead the Fuel Element Model is able to model three-dimensional vegetation optimized to simple volume shape.

FarSite software

FarSite is a model of spatial and temporal prediction of fires in various soil, fuel, and meteorological scenario conditions designed by Finney and developed by United States Forest Service, Rocky Mountain Research Station, Fire, Fuel, and Smoke Science Program. It is a software used mainly in the United States for different purposes.

One of them is the scheduling of prescribed fires: prescribed fire are fires specifically designed and triggered at low risk to burn dead fuels (trees but also shrubs).

Another use is the simulation of active fires. The simulations obtained can help to predict the possible propagation of an active fire. This supports extinguishing operations, helping to plan strategies in order to make the best use of available resources for firefighting and fire control.

It can be used also in the simulations of future fires or potential fires; this is not only for prescribed fires but also for possible natural or arson fires. The simulations can help in planning fuel reduction interventions and planning actions.

The last use is the simulations of past fires: in this case, the aim is the reconstruction of scenarios already occurred through the use of available data. This is useful for analyzing and understand the fire dynamic, to study prevention strategies such as firebreaks and where to apply them in the planning of useful firefighting strategies in possible future fires.

FarSite simulates the development of a forest fire as the shape of an elliptical wave expanding on a flat surface. In a defined period, ellipses are generated from points outlining the peripheral areas of the fire.

Their outer edge represents the new fire front, so the points from which other elliptical waves will start in the following time step. The results are different if the propagation happen in uniform or not uniform condition.

In uniform condition the wavelets have the same shape and size for keeping the outline shape as an ellipse, instead in nonuniform condition the wavelets have different size based on different features of fuel, slope, and wind.

The result is a not regular shape of fire propagation as show Figure 3.

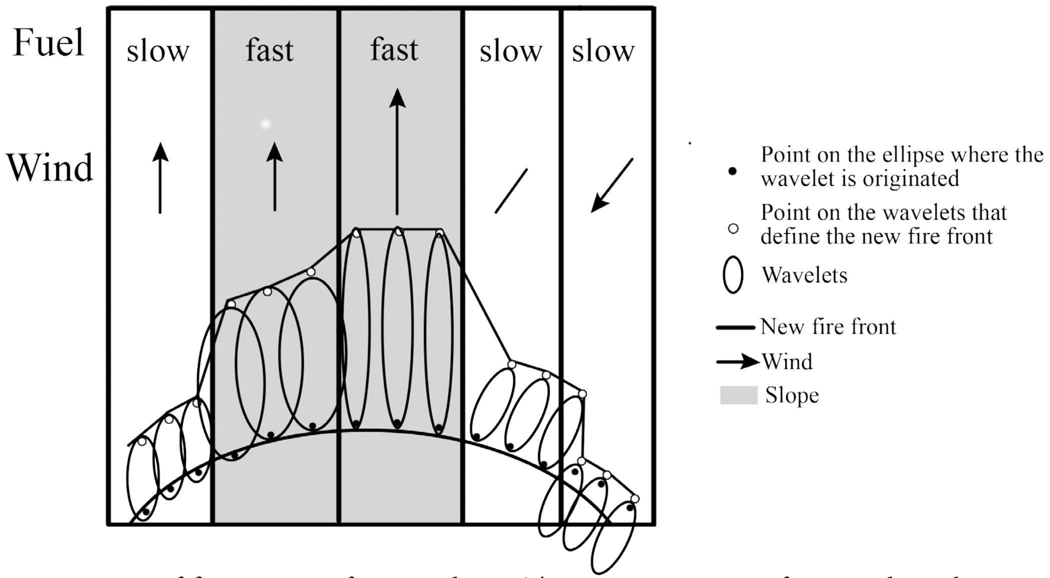


Figure 3. Propagation of fire in nonuniform condition. The propagation in uniform condition bring to similar wavelet because there are not influences, so the new firefront looks like a concentric circle. In nonuniform condition instead, the wavelets have different size based on different features of fuel, slope, and wind that modify their shape. Adapted from (Finney 1998).

This process is referred to as the Huygens principle. On the Huygens principle, have been elaborated all the calculation models of the software.

The software, in fact, is designed to use multiple mathematical models of fire propagation, which in turn are useful to simulate different aspects of a complex event such as a forest fire in order to get closer and closer to a real reconstruction.

The mathematical model used by FarSite are surface fire, crown fire, post frontal combustion, fire acceleration, spotting.

The surface fire is a fire that develops on a homogeneous fuel and with uniform wind and slope conditions. If there are trees the fire spread under the level of the canopy, without develop on a vertical level. This crown fire instead also considers the possibility of the fire turning into a canopy fire, spreading in height between the branches and leaves of the trees.

An active canopy fire spreads much faster than a surface fire as well as gaining much more power. The crown fire can be passive, then the single tree will burn. Otherwise, it is active, and it will spread from foliage to other trees).

With active fires, the rate of spread is much faster and more intense. Post frontal combustion is a model to represent what happens to combustibles with a longer burning time once the fire line has passed over. The fire acceleration considers the increase of fire propagation from an ignition point.

Finally, spotting is the occurrence of new ignitions over the front of the fire due to ashes carried by the wind. It is a very important aspect to consider especially in cases of strong wind as it could start fires even far away, suddenly changing the course and the evolution of the fire. FarSite cannot calculate the single fires but it stops at phase two, indicating as spots all the possible starting points of a new fires.

The software FarSite for running a simulation need different type of input that describe all the aspect can influence the fire for reproducing in the most realistic way the fire behavior.

Mainly it is possible to divide the inputs in three categories:

1. Landscape input: geospatial information and fuel description
2. Weather data: information about weather and wind condition
3. Moisture input: describe the amount of water in the vegetation (live or dead).

For obtain or create this kind of input there are different reference database depending on which kind of data are necessary. The database used for the Fuel Data is Landfire, a multi-partner program between three united states fire management organizations. The organization are the

United States Department of Agriculture Forest Service (USDF), the agency that administers national forests and grasslands, the United States Department of Interior (DOI), a federal executive department and is responsible for the conservation and management of most federal land and natural resources, and Nature Conservancy.

This is an organization aimed to environmental conservation that works for charitable purpose. The Landfire database handles the production of geospatial databases covering the United States territory and was created to have a complete and common data set throughout the country to support the planning and management of natural resources and fires.

The Landfire data are on a landscape scale and are used by major federal organizations. Landfire offers three main products: geospatial data, ecological models and the tools that are provided to manage the data sets and modify them.

If fuel data have one main reference database, meteorological data are obtained from the data recorded by the nearest weather stations. For the stations there are two main reference databases. The first archive is the national Fire and Aviation Management website.

The data can be read and processed on the Fire Family Plus software that extracts the necessary inputs for FarSite software simulations. The second is the RAW USA Climate Archive, managed by the Western regional climate center.

The landscape file is a fundamental file for simulation and contains orographic information provided by raster themes mainly downloaded from the database Landfire.

Each raster data must be in ASCII format and each level must have the same spatial resolution and the same size in order to be exactly overlapping.

The Landscape file is composed by various layers, same for describe the terrain morphology and some for describe the fuel.

The layers are the following:

1. Elevation: the high of the zone concerned, this data is used for the adaptation of

temperature and humidity basing on the altitude

2. Slope: the slope can have considerably affected the growth of fire and especially its shape; it is used to determine the angle of the incident solar radiation and to project the speed of spread and the surface direction.
3. Aspect: expresses, in azimuth degrees, the direction of the slope, o is the north. It is a data of considerable importance together with the slope.
4. Fuel model: physical description of the surface combustion complex used to determine the behavior of the surface fire.
5. Canopy cover: it is used to determine the average shading on the surface fuel and affects the determination of fuel moisture and the reduction factor that decreases the wind speed.

Besides these five orographic themes just described, which are essential to load the Landscape (.LCP) file and without which the simulation cannot run, there are three others considered optional but that allows the operator to simulate in a more accurate way the fire behavior.

6. Stand height is the high of the plants and influences the wind reduction factor, the position and the trajectory of the burning embers released from the burning trees during the spotting phenomenon.
7. Crown base height: It describes the vertical distance between the ground surface and the base of the live tree crownland it is used to determine the intensity threshold of the flames.
8. Crown bulk density determines the threshold of the canopy density that must be exceeded in order to observe the transition from passive crown fire to active crown fire.

The weather inputs describe the condition and are based on hourly observation.

The data are recorded by weather automatic stations and then processed by the software Fire

Family Plus for exporting the input for FarSite.

Three types of weather data are considered as follows: Weather file (.WTR), Wind file (.WND), and Weather Stream file (.WXS)

The Weather file contains daily observations of the temperature, humidity, and precipitation of the area where the reference station is located.

These data represent the weather conditions over time. The meteorological data are used by FarSite to model the changes in dead fuel humidity that occur due to different orographic and shading situations.

The Wind file describe the wind direction and the wind speed in the area analyzed. FarSite can consider the variability of wind over time, but it considers the wind constant in space. This mean that it does not consider the effects that the orography of territory and vegetation can have on wind direction and intensity.

The Weather Stream file is an optional ASCII text file. This file is a combination of Weather and Wind files. It provides actual temperature and humidity values for each hour of the observation.

After weather input it is important to consider moisture.

Moisture files are input wrote in ASCII that give information about the dead and live fuel. There are three type of files: initial fuel moisture, adjustment file and burn period.

The initial fuel moisture file (.FMS) contains values that indicate the initial fuel moisture for each model. The initial fuel moisture file provides moisture values for the fuel 1h, 10h, 100h, and the fuel herbaceous live component and woody live component.

The adjustment file shows some correction factors that sometimes have to be made to the rate of spread (ROS) simulated in FarSite because sometimes the results could be overestimated or underestimated compared to what you would have in a real context.

This kind of adjustment can be useful because people can integrate their local knowledge of the area estimating if the simulation needs to be slower or faster based on their experience. The burn period file is the last optional theme for moisture inputs. This optional file indicates the start and end time of the simulation.

Usually is used to stop the simulation during the periods that come considered inactive for the fires, like cold periods or damp nights.

Moisture content usually increases at night also in the dry season. The use of all the available options for giving precise input to the software will contribute to have a really accurate results of the simulation of wildfires.

SIMULATION OF EVACUATION PROCESS

The simulation of the dynamics of the crowd has assumed more and more important in the planning and with the increase of the capacity of calculation of the last computers, a lot of different software finalized to crowd simulations have been created.

It is quite simple therefore to have a verification of the own results replicating the own simulation on more software trying to put in light the differences between them. Currently, there are two families of models commonly used for the calculation of the time of movement: macroscopic models and microscopic models.

The macroscopic models are born from reproducing the pedestrian flow as a continuous flowing. They are more suitable in case of high pedestrian density, i.e., when the movement of the mass makes that of the individual negligible. This model considers people as particles belonging to a single group and describes the behavior not with parameters inherent to the individual but to the totality of the movement of the mass.

In microscopic models, on the contrary, the behavior of the individual is evaluated by highlighting the difference in the user profiles present in the model. The name of this type of model is Agent Based Modeling (ABM).

The Agent Based Models can also be extremely complex and are based on the presence of a series of entities, called agents, to which are assigned characteristics of size, motion, familiarity, and knowledge of the place, and each of them moves independently.

The behavior pattern of an Agent Based Model agent is divided into two phases, one of recognition of the situation and then performs what the code provides in the presence of a specific context. Besides, their decision may change over time depending on other variables in the model that change the context in which the agent has made a certain decision. For example, the agent directs to an exit, once the simulation begins that exit is no longer usable, and the agent will make the decision to move to another exit.

In an Agent Based Model it exists then an ulterior distinction according between agent base models.

If it is based on force (force-based), the behavior is based on the forces that agents exchange among themselves. These forces can be attractive, repulsive, driving, and fluctuating.

The second type is based on rules (rule-based) where the behavior of pedestrians depends on rules, an example of can be the cellular automata model recently applied to evacuation.

The shift to performance-based-design has led more and more to the affirmation of the importance of performance of the buildings.

Since these innovations were introduced, the exodus process has acquired high importance within the safety project.

The main concepts introduced about exodus are the available safe escape time (ASET) and required safe escape time (RSET).

Available safe escape time (ASET) is time interval calculated between the ignition of the fire and the moment in which the environmental conditions in the activity become such as to make the occupants unable to be safe by reaching or remaining in a safe place.

Required safe escape time (RSET) is time interval calculated between the ignition of the fire and the time when the occupants of the activity reach a safe place.

The criteria to follow is that aAvailable safe escape time (ASET) greater than required safe escape time (RSET) then the time in which the conditions for which it is possible to evacuate remain is

always greater than the actual time to evacuate the entire building.
The evacuation process is divided into several phases that can be summarized as the following three: Time of fire detection, General alarm time, and Evacuation time.
The detection time is determined by the type of detection system and the fire scenario. It is the time it takes for the automatic detection system to detect the fire, the general alarm time ta is the time between the fire detection and dissemination of information to the occupants of the general alarm.
The evacuation time is divided in pre-movement and movement activity time. The first one is the time needed for the occupants to recognize they are in danger and to perform a series of activities before the movement to the safe place. This phase often takes up most of the total exodus time.
The movement time is the time taken by the occupants to reach a safe place after the termination of the pre-movement activities and it is calculated according to the occupants' distance from the exit, their speed (this is determined by the type of occupants), and the capacity of the escape routes, due to geometry, size, height differences, and obstacles.
The use of crowd simulation software is finalized to minimize the Required safe escape time (RSET) values.

Evac software

Evac is an extension of Fire Dynamic Simulator developed by the National Institute of Science and Technology (NIST) and the VTT - Technical Research Centre of Finland.
It adopts the Social Force model but what makes EVAC different from other exodus simulation software is the ability to integrate it with the fire and smoke model, so it is able to consider

the conditions posed by the fire as a function of the simulation. The main characteristics that influence this aspect are first the reduction of the visibility. Due to it the occupants suffer a slowdown according to the concentration of the smoke.

It is possible to set the height to which the occupant is influenced by the presence of smoke. The second factor is the presence of carbon monoxide: occupants may be unable to move according to FED (Fractional Effective Dose). So, when the presence of carbon monoxide becomes higher than people's tolerability.

As last there is the response time. It is possible to set the time for the promotion of the agents, however, the start of the exodus can also be given according to the smoke concentration. However, it is not possible to set a reaction time after the triggering of fire protection systems.

Agent modeling Evac considers a series of physical factors that are created in a crowd movement to realize a realistic simulation.

Most of these factors are given by panic as, for example, friction forces between agents or between agents and geometries, social and psychological.

The path of each occupant is established by an equation of motion where the position of the agent depends on the simulation time, the force that the agent exercises on its contour, the mass, and a random fluctuation component.

To define the exit to which the agent will move, the software considers the solution of the choice as a case of optimization in which the occupant goes to the door that makes its evacuation time minimal.

The choice of the exit is established on three criteria: visibility (the agent can see the door from his position), familiarity (the agent even if he does not see the door is aware of its existence) and conditions of disturbance (the presence of smoke that may prevent them from seeing the exit or of carbon monoxide that may make them unable to move).

The agents are represented by three circles as shown in Figure 4.

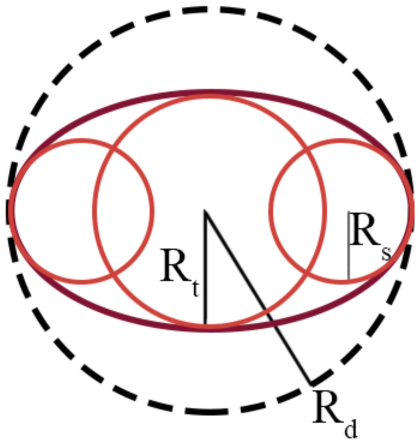


Figure 4 Geometry of an agent in the EVAC model. The geometry is based on four circle and one ellipse.. The speed, dimension, and other parameters of the default profiles of Evac agents are based on the ratio between these three radius parameters.

One larger in the center and two smaller ones arranged to form an ellipse according to the Langston model (Langston et al. 2006).

Also, lethal threshold values for the agent are included in the definition of the disturbance conditions.

If the agent encounters them on his way to the exit, the user remains stationary, i.e., his decision is diverted to an exit without preference. Exit without preference means that the agent cannot go towards it because he cannot go towards an exit that he does not see and does not know.

The types of agents that EVAC models can be based on four types of behavioral patterns, conservative, active, herding and follower.

The active and conservative agents are the more involved directly in the evacuation because they are able to remember and look for an exit, instead herding and follower mainly wait for seeing where other agents go and then that follow them. The follower agent if one of the alternatives is better as an evacuation time the follower agent will go there.

MassMotion software

MassMotion is an advanced pedestrian simulation software based on social force model developed by Oasys and it is one of the advanced tools in the field of crowd simulation. It is a BIM compatible modelling software and has the possibility to program individual personalities and behavior for each agent that can also respond to changes in real time, for example choosing to take another escape route.

Finally, MassMotion report in a variety of ways with visually pleasant graphics, tabular and data-driven outputs, all presented as easy-to-understand graphics and visuals. The MassMotion scene is characterized by some basic concepts.

The software uses them to model all the object in the space, classifying them according to their own function. In this way the agents know how to move and how to behave in front of an obstacle or of a stair.

Also, some feature of them can be modified basing on the type of issue they are in front of. For example, stairs are modeled as surface, but the agent know that, when he is moving on a surface classified as a stair, his speed will be reduced.

The way objects are classified can influence the route choice, the speed, and the movement so it is important to be careful and assign the right type of object to each element.

The basic classification of the elements in the scene is: floor, link, stair, ramp, escalator, path, elevator, portal, and barrier. Floor is the main object in the scene because represent the areas where everting else is located in the model. Also define the space where agents can move.

There can be multiple floors on the same level and each of them defines a precise walkable area and the movement are constrained by the floor boundary.

Link, stair, ramp, escalator, paths, and elevator are tools for guaranteeing the connection between floors.

They have different feature and influence the speed and the movement of the agents.
The portals represent entrances or exits. They indicate in the model or the areas where people are generated or the destinations where people can go to escape Finally, the barriers are all the solid obstacles in the model.
MassMotion is an Agent Base Model. This means that each agent can have its own behavior and the ability to react to the environment around. The modeling of the agent is characterized but some parameters, the characteristics defined by profile, the scheduling of the actions, the tasks that the agent must do before going to the assigned exit.
The navigation system determinate the best way to complete the task assigned and arrive as soon as possible to the designed exit. The decision is evaluate based on the distance and the congestion. Also, if a route has been chosen, the agent re-evaluate the decision periodically based on the changes in the environment.
The movement of the agent is influenced by social forces. Those forces are generated by the environment around the agent for each moment of the simulation by the direction, the location, the obstacles around, and the movement of other agents.

VIRTUAL REALITY MODEL USING UNITY SOFTWARE

Virtual reality simulates, through electronic technologies, a real scene. Today with the progress of technology the demarcation between virtual and real is fast becoming more and more labile in how much the new visualizations and graphical abilities are more and more approaching a deep realism.

Although it is a concept that many consider extremely modern was introduced almost sixty years ago, precisely in 1962, by Morton Leonard Heilig) who patented a device called Sensorama, a machine for see movies with, a multisensory involvement with immersive and realistic visualization.

The modern concept of virtual reality today is much more extensive it does not stop at simple visualization but also interaction with the virtual environment and movement within it. A first definition of the modern concept of virtual reality was given by Milgram and Kishino (1994).

The concept of the transition from real to virtual is inserted on a continuous line (reality-virtuality continuum). The concepts of "Real environment" and "Virtual Reality" were positioned at the two ends of the line, while the concept of "Mixed reality" formed by "Augmented Reality", "Augmented Virtuality" and a thousand nuances that can be created between these four areas. The first one, the reality is the world as we see it with our eyes, without any filter.

Augmented Reality (AR) means and enrichment of reality, the user is placed in a real environment with virtual additions. With the augmented virtuality instead, the user moves in a virtual

environment but is still able to interact with real information even if not prevailing.
One of the applications is as an example the recognitions of the hands where the player can see its own hands projected into the virtual reality. The virtual reality has as a purpose that one to make to immerse the customer in a fictitious reality, an alternative to the real world, realized purposely and in which it is free to move, to touch objects, to move them and to interact with the elements present in the simulation.
It is necessary to distinguish two types of virtual reality, immersive and not immersive. The not immersive virtual reality is when the visual impact between the user and what the user sees is limited to the flat visualization on a screen.
This mode certainly has a lesser emotional and sensory influence on the person because there are still several barriers that immersive simulations break down.
The immersive virtual reality allows, instead, through tools such as platforms and appropriate viewers, to dive completely into the virtual mode and not look at it from the screen. The viewer is traced by sensors and follows every single movement of the user's head, increasing the involvement and the feeling of realism.
Moreover, losing every reference with the surrounding world, it is very easy to recognize as a unique reference system that of the virtual world. All the interactions are managed by remote controls, and recently platforms have been developed to simulate movement.
The viewer follows the movements of the user but would require a very large space to move around the virtual world, as well as being dangerous because it is impossible to perceive obstacles. Therefore, many simulations have movement commands to manage through remote controls to facilitate the movement.
The last platforms, however, give the possibility to connect to a harness and wear sensors on the feet able to recognize and reproduce the movement without moving.
Lately several software of various types, including architecture and engineering, give the

possibility of virtual reality visualization of the realized project or built simulations (for example the software for the simulation of exodus Pathfinder developed by Thunderhead Engineering offers the possibility to identify with one of the occupants and live the simulation in the first the software for the simulation of exodus Pathfinder developed by Thunderhead Engineering offers the possibility to identify with one of the occupants and live the simulation in the first person).

This software gives the possibility of an immersive experience but is not able to enter the field of design and development of a simulation in which it is possible to interact with the environment. For this aspect, the two free software, if not used for commercial purposes, are Unity3d software and Unreal.

They are both software born for the development of videogames and written in C++ code, therefore, also to implement a simulation it is necessary to write some codes using C++ as a programming language. In the merit of this thesis, the software used to develop the final simulation has been Unity.

Moreover, as mentioned before, tools are needed to take advantage of the immersive visuals and movements.

Usually, they are systems with different peripheral devices traced by two sensors that must be installed in the room where they are used in a more elevated position so that no movement vein hidden by obstacles. As for the viewers, the most famous instruments available on the market are Oculus Rift and HTC Vive.

CH. 4

CASE STUDY I

THE MASCAGNI SCHOOL

DESCRIPTION OF THE STRUCTURE

The school Pietro Mascagni is a comprehensive institute divided into various plexuses into the municipalities of Melzo and Liscate in the province of Milan. The school manages two kindergartens, two elementary schools, and two secondary schools. The building studied in this thesis is the plexus of the secondary school Mascagni located in Melzo at Via Pietro Mascagni 11. The building was constructed in 1976 as many school buildings in Italy that was built in the same period.

The structure of the building is reinforced concrete and is divided into three blocks: classrooms, gym, and a third block where there is a canteen on the ground floor and an auditorium on the second floor.

The block with classrooms is on three floors, two above ground and one underground where there are the foundations of the building.

The ground floor is dedicated to laboratories and offices while all classrooms are located on the second floor.

The complex, however, does not border directly with other buildings, on the contrary, it has a green area surrounding the building on all four sides. In the school there are twenty-four classrooms, a library, two archives, offices and twelve laboratories and there are also outside some sport fields.

Figure 5 and Figure 6 show the structure of the building.

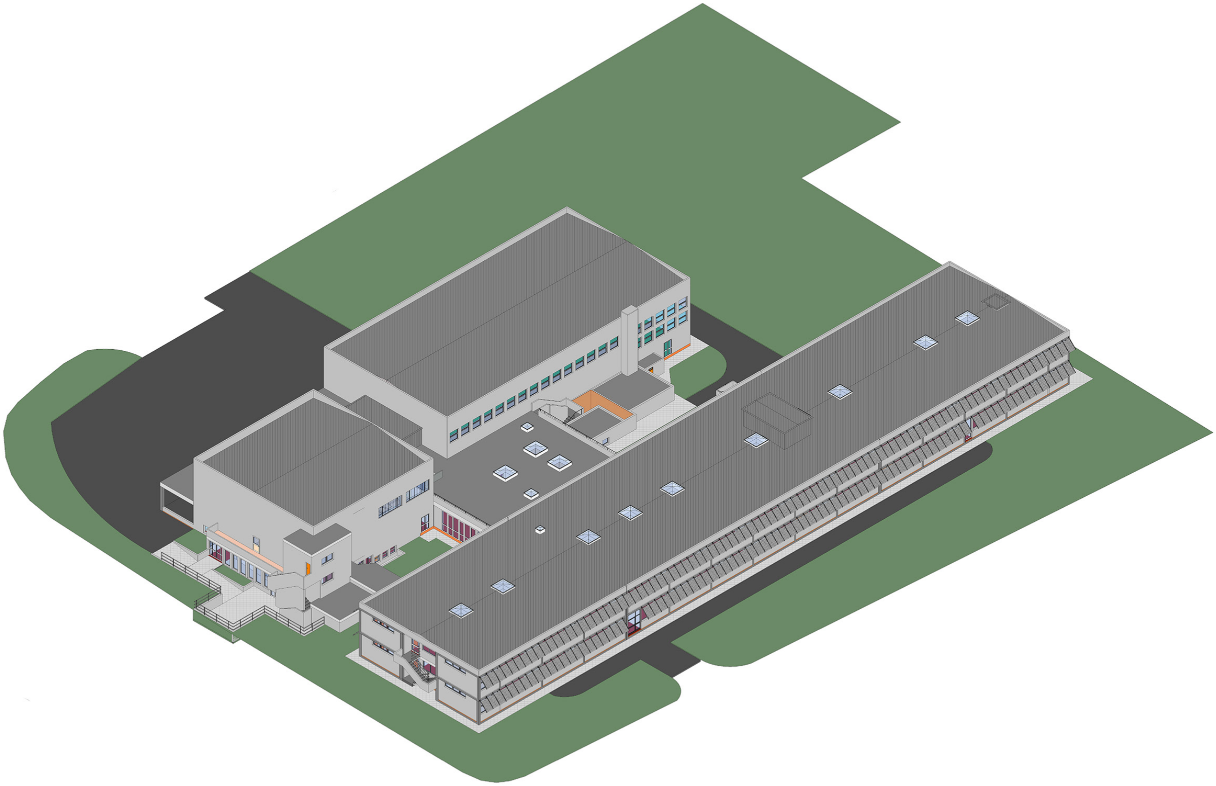


Figure 5 Axonometric view of the school Building. In the view is possible to notice the structure divided in three separate blocks: the classroom is the longer one, then there are the gym and the canteen/auditorium. The three buildings are connected only on the ground floor level by a connection.

A

B

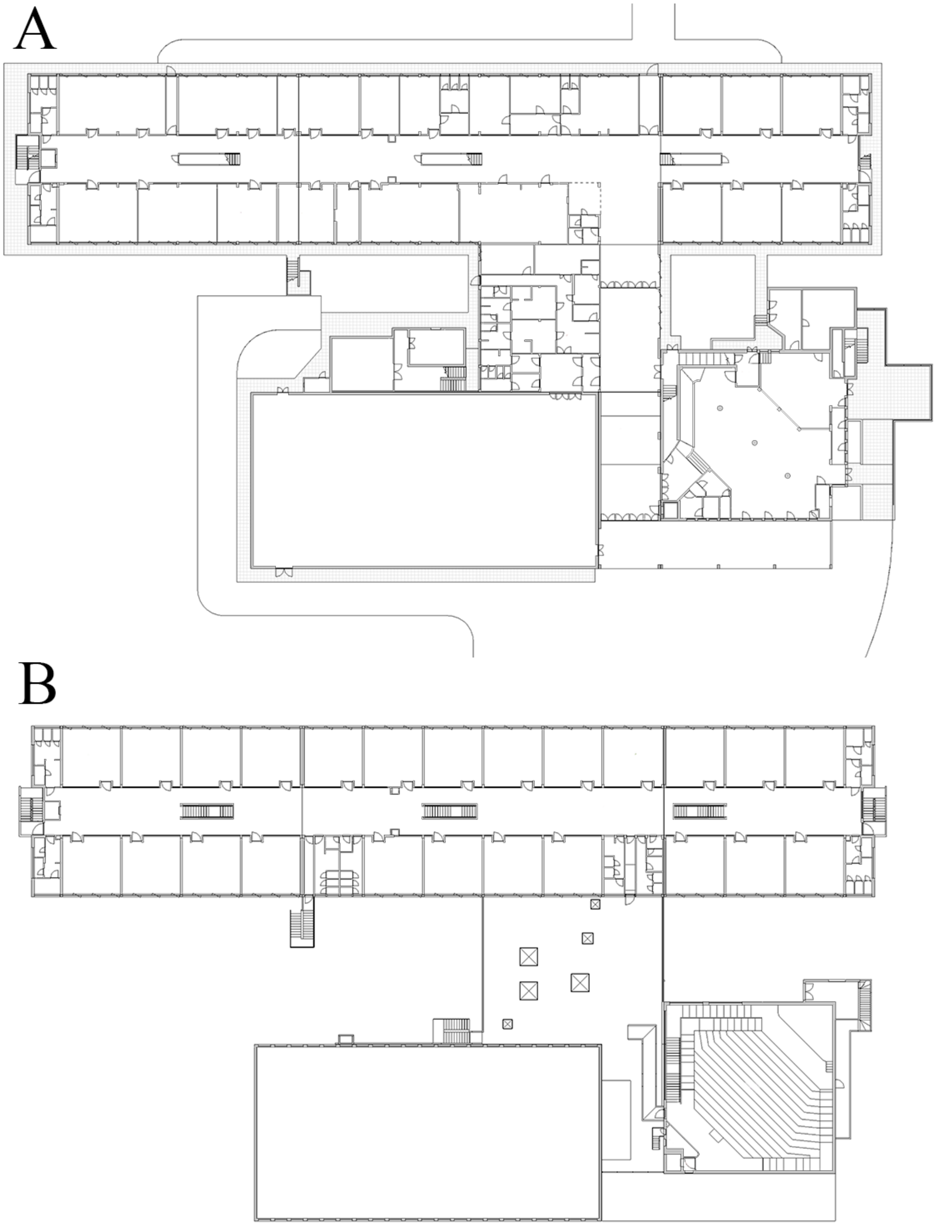


Figure 6 Ground floor (A) and first floor (B) plan of the school building. On the ground floor of the main block of the school there are only laboratories and administrative offices. All the classrooms are on the first floor.

The school is not at its maximum capacity to contain people, only sixteen classes out of twenty-four are occupied (four for the first year, six for the second year, and six for the third year).
For simplifying the analysis, it was chosen to focus on the main block, leaving aside the other two buildings (gym and auditorium/canteen) that are compartmentalized and therefore not directly connected to the main block in case of fire.
Also, the classrooms' block is where the most part of students are all the time they spend in school.
The new fire prevention code (D.M 2015) introduced the risk profiles. They are indicators for attributing to each area of activity the appropriate performance for the reaction to fire of the materials and the necessary firefighting measures.
The profiles are three and define the three main categories to be preserved: R_{vita} for the protection of people, R_{beni} for the safeguard of goods, and $R_{ambiente}$ for the protection of the environment.
The R_{beni} and $R_{ambiente}$ profile risk it is not considered because the school does not have any historical or strategical relevance and does not contain any material dangerous for the environment.
The R_{beni} and $R_{ambiente}$ profile risk it is not considered because the school does not have any historical or strategical relevance and does not contain any material dangerous for the environment.
About the R_{vita} profile it is important because it serves to define a number of factors related to the exodus such as the size of the corridor and the width of the exit routes and it is defined by two following criteria: δ_{occ} indicates some prevailing characteristics of the occupants inside the building and δ_a indicates the prevalent fire growth characteristic speed.
The occupants belong to the A-profile (according to the tab G.3-1 in the D.M (2015), they are awake and familiar with the building.
For the fire speed, instead, according to the environment should be applied different values of δ_a, 600s (slow) for example for places like the gym, 300s (average) for classrooms at 150s (fast)

for computer labs. So, the R_{vita} profiles that emerge are A2 and A3 according to table G. 3-3 (D.M 2015) . Depending on the profile risk assigned there are different requirements in the project. Table 2 report a summary of all the exodus features of the school according to (D.M 2015) section S4.

Table 2 Summary of all the exodus features of the school

Performance level I	The occupants reach a safe place before the fire leads to incapacitating conditions in the areas of activity crossed during exodus
Crowding >500	Minimum number of exits: 3
Maximum length of the escape routes L_{es}	<45 m
L_u 4,60 mm/person (Unit Width determined by the risk profile R_{vita})	Δt_{coda} 240s (maximum waiting time before evacuating)
L_u 4,75 mm/person (Unit Width based on number of floors (2))	Δt_{coda} 240 s (maximum waiting time before evacuating)
Angle between two exits	>45°

The school model was initially created using Blender to generate the geometry and then written manually using a text editor.

The geometric characteristics of the objects in the simulation must adapt to the base grid of the model since every cell presents uniform values and information.

This means that if an object turns out to occupy half a cell this will come adapted and will fill all the cells in the calculation, or it could come cut from the simulation.

For this, the geometries must be the simplest as possible and optimized to rectangular shapes in fact for example any whole geometry in L shape or perforated would be simplified in a rectangle. That is why the first step in model construction was to build an optimized 3D model in rectangular shapes. The model has been created starting from the draw in Blender, decomposing every object in order to be red by FDS as similar as possible to reality.

In order not to make the geometry too heavy, some rooms with a more complex shape such as bathrooms were represented as solid cubes and not modeled inside.

Afterward, the basic file with the geometry was created and exported from Blender through the BlenderFDS extension. In this way, it was possible to obtain the text file for compiling the Fire Dynamic Simulator code with already all the geometries written by Blender.

The rest of the simulation was processed manually using a text editor. Figure 7 shows how the building geometry has been simplified.

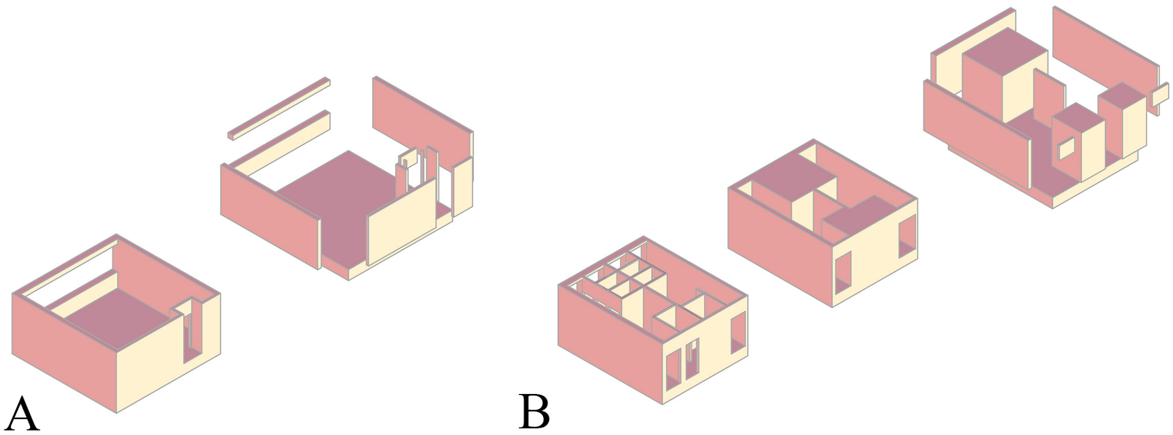


Figure 7 Decomposition of school in simple geometries. The examples reported are one classroom (A) and the bathroom (B). For complex subdivision of the space, as happen in the bathroom, for optimize the calculation time, the space has been simplified in cubes.

All the simulations are located on the first floor because is where most part of the student are in the day and where there could be some problems related to the correct evacuation.

The fire is simulated in four different scenarios. The four fire scenarios due to four different ignition point have been chosen in order to have four situations of availability of emergency exit. The choice of the scenarios is for verifying the redundancy, request in the exodus section of the Fire Prevention Code (D.M. 03/08/2015 S.4.8.4).

The redundancy check is made to verify the minimum width of the exit ways in case one is made not usable by the fire. For this verification, the various exits must be made unavailable one at a time and then verify if the overall width of the remaining ones is sufficient to allow the evacuation of the occupants.

The scenarios are:

1. Scenario A: The fire start in a classroom, all the emergency exits are available.
2. Scenario B: The fire start near the central exit door. All the student must evacuate through the left door and the right door.

3. Scenario C: The fire start near the left exit door. All the student must evacuate through the central door and the right door.

4. Scenario D: The fire start near the right exit door. All the student must evacuate through the central door and the left door.

The four scenarios are visually represented in Figure 8.

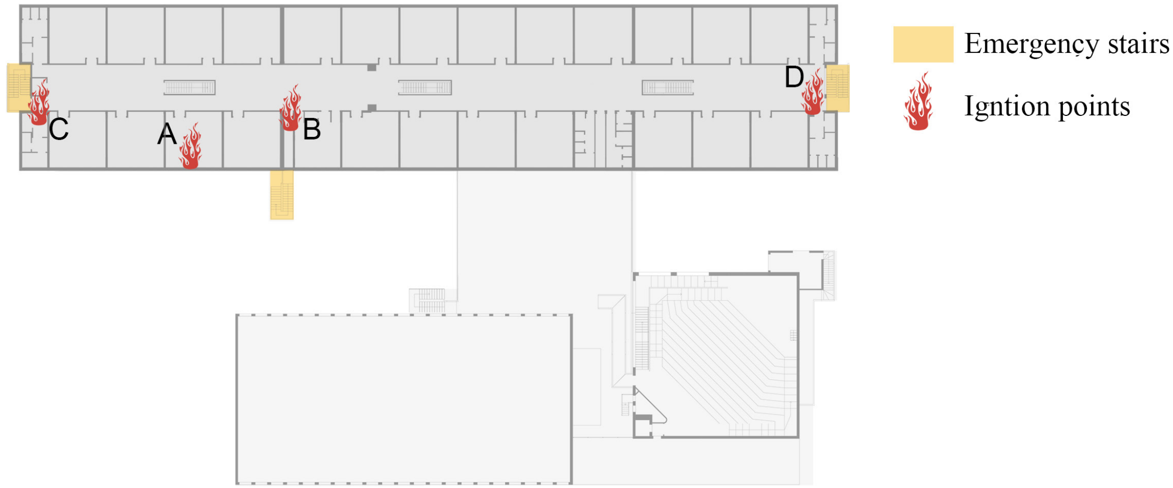


Figure 8 The map shows the four fire scenarios. The scenario A fire is located in a random point in the school, instead the other three are in strategic point for make the nearest emergency exit not usable. In this way in scenarios B, C, and D only two exits will be available.

The reaction used for simulating the fire is generated by a plastic bin, a possible fire event in school building. The heat release curve is from experimental data taken from (Stroup and Madrzykowski 2003). The use of experimental data it is an important in order to create a realistic fire propagation. The curve has been realized in the Fire Dynamic Simulator code creating a RAMP of heat release. RAMP it is a time depending input in Fire Dynamic Simulator and it allows to associate to each moment of the simulation a value of the heat release rate curve for modeling the reactions more similar as possible to reality. Figure 9 shows how the smoke propagate in the school through the time.

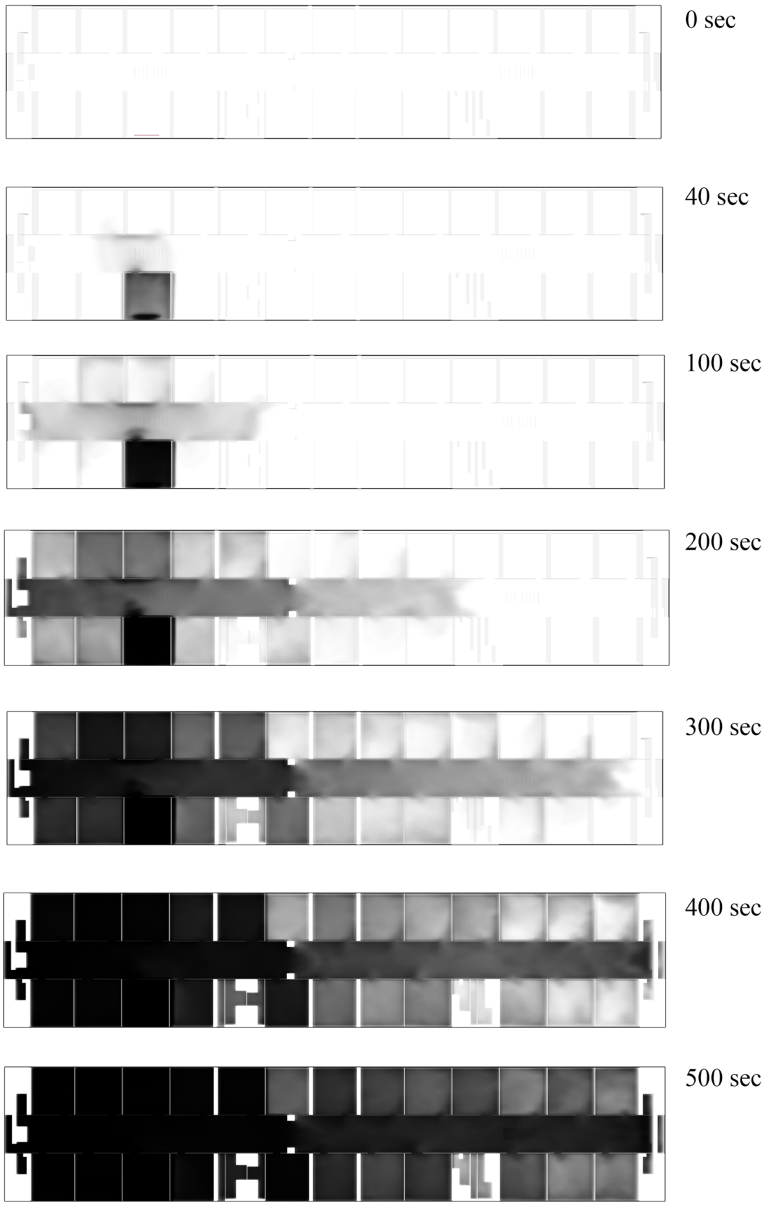


Figure 9 Simulation of fire and smoke propagation with timestep ; The fire simulated is the Scenario A and the reaction utilized is the fire of a plastic bin.

SIMULATION OF EVACUATION PROCESS

The first step for simulating the evacuation is establish the crowding of the building. The actual number of students in the school provided by the school itself is underestimate because not all the class are utilized, so the real capacity of the school is more than the number of pupils they have now. Therefore, the number of occupants will be calculated as the theoretical crowding, according to the procedure indicated by fire regulations. The maximum crowding is calculated by multiplying the crowding density (table S.4-12 DM 03/08/2015) by the area of the room.
Table 3 summarize the factors considered for calculating the crowding.

Table 3 Crowding according to the table S.4-12 (D.M03/08/2015)

Floor	Room	Surface (m2)	Crowding density	Theoretical crowding
GF	A/V Lab	61.4	0,4	25
GF	Painting Lab	75.7	0,4	30
GF	Music Lab	44.8	0,4	18
GF	Generic Lab	303.7	0,4	121
GF	Science Lab	46.0	0,4	18
GF	Computer Lab	121.5	0,4	49
GF	Library	81.9	0,2	16
GF	Drawing Archive	42.7	0,2	9
GF	Archive	86.0	0,2	17
GF	Office	154.2	0,4	62
GF	Professors' Room	30.5	0,4	12
GF	Reception	18.9	0,4	8
1F	Classroom	1070.9	0,4	428

The total number of people present in the school is 813 considering all the facilities, but some of them are occupied sporadically by people already present in other counts as students and teachers already considered in the classroom calculation.

For this reason, the number of occupants considered will be the total net of the number of people counted in the rooms not considered common spaces such as classroom. Instead laboratories, for example, are considered common spaces. The maximum crowding is then 536 people.

From the comparison of the data, some differences emerge in fact in the theoretical crowding the average of people in a class is around 18/19 individuals, in reality, the cashiers are composed of an average of 22/23 individuals plus the eventual professors present in the classroom at the moment.

To guarantee the possibility of evacuation even in the most severe situations, a certain number of independent exits must be guaranteed.

Independent exits mean that the possibility of them becoming simultaneously unusable is minimized. Independent exits are, for example, external or protected exits, while those in the same compartment without any protection are not considered independent.

To avoid the development of localized overcrowding the number of outputs must be at least three according to the table S.4-15 from DM 03/08/2015.

The mode of exodus in this case is the simultaneous exodus (DM 03/08/2015 S.4.1.3.a) generally applied in all schools.

Once the number of occupants is defined the following step is model the evacuation. The two-software used in this thesis are MassMotion and Evac, both are Social Force Model.

There are four scenarios simulated that, as for the fire create different situation of evacuation:

1. Scenario A: All the emergency exits are available.
2. Scenario B: All the student must evacuate through the left door and the right door.
3. Scenario C: All the student must evacuate through the central door and the right door.

4. Scenario D: All the student must evacuate through the central door and the left door.

In MassMotion for optimizing the overlapping with the simulation with EVAC the base three-dimensional model it is the same used for building the geometry in Fire Dynamic Simulator.
Once the model has been imported the basic surface such as floor, obstacles and stair have been assigned to the single object.
The portals in MassMotion are one of the basic tools because they can be or the point where agents are originated or the point where they must go for evacuating.
In the model have been created twenty-four portals for originating the agents, one for each class and three portals for the exits.
The simulation is limited to the first floor because it is the more subject to crowding effect due to the fact that most part of the students are there. The profile of agent used are basically two, one for the children and one for the professors.
It is not possible to set the professors profile to wait that all the students leave the classroom as they should do, so to their profile have been applied a delay of some seconds.
The pre-evacuation time is represented with a log-normal distribution (min = 4 s, max = 166 s, average = 41 s, STD 35 s) based on a series of experiments conducted in Spanish schools with the objective of acquiring information on the fundamental parameters that affect human conduct in the event of evacuation (Cuesta and Gwynne 2016).
The log-normal distribution is the one generally used to best represent the impact of the Social influence in its initial phase, and the response of people who decide to activate the exodus late.
The speeds of the different type of agents are proposed in the literature (Thompson and Marchant 1995) and in order to represent different categories of people as teachers and pupils have been considered as log-normal distributions.
Table 4 show the values used for define the agents.

Table 4 Speed of the agents introduced in MassMotion. The values are referred to Log Normal distribution. (Thompson and Marchant 1995).

	Max	Min	Average	STD
Professors	1.55	0,95	1.25	0.25
Students	1.2	0.6	0.9	0.2

For build the simulation in EVAC the base file was the same of the fire simulation for the geometry.

For simulating the evacuation, it is important to set an evacuation grid, and the mesh where the agents are been created.

After having set one mesh for each classroom there have been chosen the agent's profile. The default agent profiles in EVAC depend by the three values of the geometry of the agent shown in Figure 4.

The size of the geometry and the speed at which the agent moves are classified into five user types as show Table 5.

Table 5 Features of the type of agent in EVAC (Korhonen and Hostikka 2009)

PERS_ID	Rd (m)	Rt/Rd	Rs/Rd	Ds/Rd	Speed (m/s)
Adult	0,255 ± 0,035	0,5882	0,3725	0,6275	1,25 ± 0,30
Male	0.270 ± 0,020	0,3704	0,3704	0,6296	1,35 ± 0,20
Female	0,240 ± 0,020	0,5833	0,3750	0.6250	1,15 ± 0,20
Child	0,210 ± 0,015	0,5714	0,3333	0,6667	0,90 ± 0,30
Elderly	0,250 ± 0,020	0,6000	0,3600	0,6400	0,80 ± 0,30

In this case the profile chosen for the simulation are Child for the student and Adult for the professors.

To define the exit to which the agent will move, the software considers the solution of the choice as a case of optimization in which the occupant goes to the door that makes its evacuation time minimal. The choice of the exit is established on three criteria.

If the agent can see the door from his position (visibility), it is a condition influenced by the presence of visa obstacles or the presence of smoke.

The second criteria is the familiarity, so, if the agent even if he does not see the door is aware of its existence and the last one is the conditions of disturbance.

Exits are categorized into seven types.

Table 6 shows in which order an agent would choose his way out based on the criteria explained above.

Table 6 Preference order of the agents (Korhonen and Hostikka 2009)

Preference order	Visibility	Familiarity	Disturbing condition
1	YES	YES	NO
2	NO	YES	NO
3	YES	NO	NO
4	YES	YES	YES
5	NO	YES	YES
6	YES	NO	YES
No preference	NO	NO	NO
No preference	NO	NO	YES

Each class have been associated to the nearest exit, so the agents can consider the familiarity only to one exit. In case that exit is not available due to the fire they can count only on the visibility of the other or follow other agents.

Among the three exits, two have a good visibility because they are in the corridor (left and right exit) but the central one it's hidden so, if the agent does not know its location he cannot arrive to it with the visibility criteria.

Another issue of the central exit is that it is located at the end of o tight corridor, so it encourages congestion phenomena.

Another aspect that the EVAC simulation considered is the interaction with toxic gases through the fractional effective dose (FED) model.

Some agents could be not able to finish the evacuation due to the exposition to carbon monoxide and dioxide. This is, in fact, considered according to Table 6 a disturbing condition.

ANALYSIS OF SCENARIOS AND RESULTS

MassMotion offers a high number of outputs. They can be maps, graph or table. Here are reported some of the most significative data that show the dynamic of the simulation.

The maps in Figure 10 are the representation of the agent count. It means that the color represents the number of agents that crossed each point.

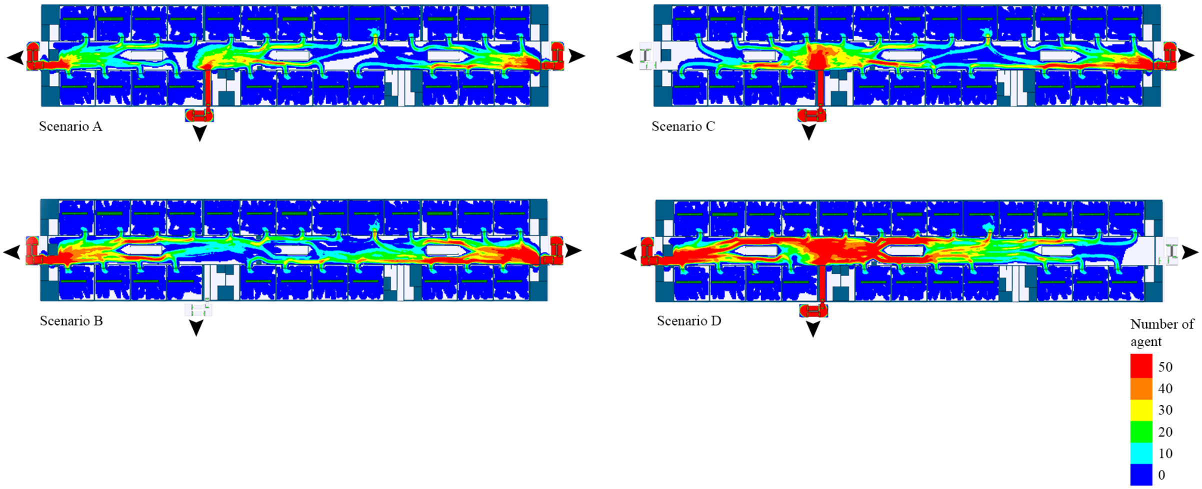


Figure 10 Agent count maps for different scenarios. The red parts are the areas more congested. It is possible to see the difference due to the different availability of the exits.

In the simulation shown in Figure 10 it is evident the difference between the Scenario A where all the exit doors are available and the other three. Scenario A, in fact looks more equilibrate and the crowd is well distributed.

The more interesting scenario is scenario D where it is possible to see an overcrowding in more than half corridor. Scenario B and Scenario C look more congested compared with Scenario A but the crowd id divided between the two available exits in a more functional way.

Figure 11 show through a graph the different timing in evacuation scenarios.

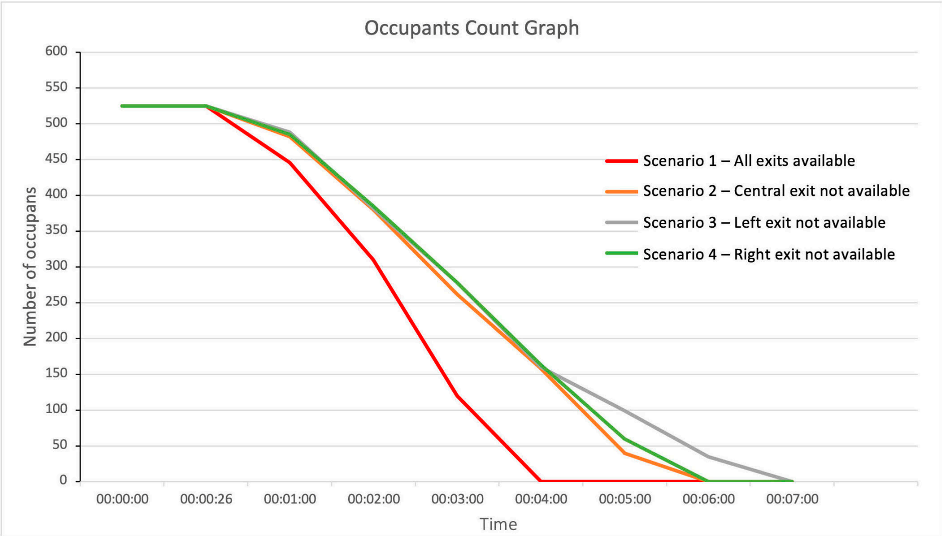


Figure 11 Occupants Count Graph. It is evident the difference between the Scenario A and the others. Scenario D show an increase of the evacuation time compared to Scenario B and C even if all of them have two exits available.

The evacuation time, as show Figure 11, change in function of the scenarios. Obviously in Scenario A, where all the exits are available, the evacuation time is less, then we have the others where the evacuation time increase.

It is interesting to underline the evacuation time of Scenario C. The other two scenarios with only to exits available have a total escaping time quite similar, instead scenario C it is almost one minute more than the others.

In fact, it is the same scenario that in the agent count maps (Figure 10) looks more congested. This can be due to the location of the central door that is a bit hidden from the main corridor. Besides, even if in the maps Scenario D looks the more congested one, the evacuation time is lower than scenario C. Table 7 show the evacuation time for different scenarios

Table 7 Time of evacuation for different scenarios

Scenario	Total time (MassMotion)	Total time (EVAC)
Scenario A	4:02 min	6:28 min
Scenario B	5:37 min	5:04 min
Scenario C	6:39 min	7:13 min
Scenario D	5:55 min	6:33 min

A common factor between the evacuation time is that, among the scenarios with only two doors available, the one without the central exit have the shorter evacuation time, due to the absence of the congestion the use of that door create in the corridors.

The results between the two software are in same aspects similar, for example the scenario with the highest evacuation time is the scenario C (Left Exit not available).

The difference between the two results are related also to the presence of smoke and his influence in the agent speed that in the EVAC simulation is lower than MassMotion. Besides the simulation in MassMotion have only the number of exits as constraints, instead Evac have also the smoke and the reduced visibility due to it.

The fact that in EVAC simulation there is not all the difference between scenario A and the others indicate that the influence of the smoke is much more intense than just the evacuation routes.

Moreover, the smoke in scenario 1, even if it was not planned, make one of the exits no longer available so the agents when they realize that it is not possible use that exit, try another path. Thus, the huge difference between the two values can be due to multiple factors.

EVAC is also able to consider the fractional effective dose (FED) model and the effects on the agents, if the index on the agent is more than one that agents will be no longer able to evacuate. In this simulation in none of the agents this happened because the highest value reach was 0.32.

The use of this two software can put in evidence the difference in the evacuation process in presence and not of smoke.

The smoke in fire have a huge influence on the people because of the reduced visibility, walking on a low level, the toxic gases effects to the body and the heat transported by the smoke.

For these reasons certainly the use of the EVAC simulation is the best one considering the propose of simulate a fire emergency scenario in virtual reality but there is no way to export the agent model from EVAC to Unity3D software, so for the virtual reality scenario the simulation used is the MassMotion one because it is possible to export easily one output directly connected with Unity.

SIMULATION OF FIRE EMERGENCY SCENARIO IN VIRTUAL REALITY

The simulation model was built in Unity 3D. The objective of the use of Unity in order to realize this final simulation is to put together various types of input that otherwise would be difficult to combine between them because of the different origin.

The three main aspects to put together are three: the geometry of the building realized on Revit, therefore a BIM model, the smoke simulation realized on FDS, and the exodus realized on MassMotion.

The scenario of the building is that of the Mascagni school whose model was imported into Unity from the existing BIM model created on Revit. There are several ways to import the model into Unity.

The easiest is to use the Tridify plugin, which was built to import BIM models into Unity. From Revit, you need to export a .ifc file, and then upload it onto the plug-in website, which will convert it and import it directly into Unity through the asset linked to the account.

Tridify is a priced plugin, but with several free trial imports available, it has been chosen for this option.

Surely the use of Tridify has greatly simplified the import work, which otherwise would have had to go through several conversion steps (for example through 3ds Max software). In any case, it is also possible to proceed in different ways. Importing through Tridify allows you to manage the model, the lighting, and the materials in a fairly simple way.

The next step was to figure out how to convert the output provided by Fire Dynamic Simulator into a three-dimensional animation and import it into Unity.
This part was the most complex to do given the difficulty in finding a link between the Fire Dynamic Simulator outputs and software that could convert them into a format suitable for three-dimensional visualization and the lack of sources or papers that could provide an adequate solution for this problem. After several attempts, in the end, a working workflow emerged with which it was possible to implement the model with smoke propagation. The process started by trying to understand what kind of Fire Dynamic Simulator output it could provide, and which could be compatible with other software. In this regard, it was used the Plot3D output, a format developed by NASA and it is possible to process them in many computational fluid dynamics (CFD) software to display the results.
A line &DUMP was then added to the code without any adjustment to the default settings, setting the creation to two files per second. The files determine the number of "frames" that the program will create.
A higher number of files will make the animation much smoother, but it is important to consider that these files take up a lot of space and because of their size they risk slowing down the data processing process.
t has also been added to the command &DUMP to write the XYZ file, which is necessary for further processing. The XYZ file contains information on coordinates and orientation.
Once these files were obtained, they were imported into a fluid dynamics analysis program to be processed.
The plot3d files can be read in three ways by computational fluid dynamics (CFD) programs: 2D Contours, Vector plots, and Iso-surfaces. The program used in this case is Paraview.
Paraview is a cross-platform open-source software for scientific visualization developed by Sandia National Laboratories, Kitware Inc, and Los Alamos National Laboratory. First the .XYZ

file was imported as PLOT3D reader and in the related options panel, all plot3d files created by Fire Dynamic Simulator have been selected. Once they were imported, they were displayed as isosurfaces using the density value as a reference value for creating the contour. In this way, the same animation of Smokeview has been recreated on the Paraview software, but by a surface defined by a mesh.

Although on Paraview it can be displayed as animation this can only be exported as video. However, it is possible to export the animation as a sequence of three-dimensional objects, each object corresponds to a static three-dimensional frame of the shape of the smoke cloud at a given time of the simulation.

These frames are exported by Paraview in .obj format. The following step was then to put all the frames together in a single sequence.

This process was done on Blender. Blender is a free software for 3D modeling and animation creation. All objects have been imported into Blender as a sequence thanks to the OBJsequence plug in. The first big problem identified was the fact that Unity only reads animations with bones thanks to which movements are recorded and can then be read by Unity. It is therefore not possible to import a frame-by-frame animation.

The solution to this problem was to create an alembic object (.abc). This type of animation consists of a single file and is an already baked animation, which means that it is a finished object and on Unity it can only be reproduced but not modified. The animation was made with the help of another plugin, Sverchok. This plugin is a parametric tool that allows you to manage geometry with node tree functions. Using the functions provided by this plugin a command tree has been created to synthesize the sequence of objects in a single file.

This file was then exported as an alembic object that can be imported to Unity.

Before exporting it, it is important to add a Displace modifier and set it to 0. On Unity it is first necessary to install the AlembicForUnity asset.

Once installed and imported the .abc file it must be inserted inside the scene. First it is necessary to create a timeline and add an Alembic Track function. From the Alembic Track it is necessary to insert an AlembicShotAsset with the .abc file.

After these steps it is possible to import the file in the scene and the animation will be activated when the program is started in Game mode. On Unity is still allowed to edit the texture and set some parameters including the animation playback speed and if desired it will be activated later than the beginning of the game mode. Figure 12 shows the smoke simulated in Fire Dynamic Simulator imported in Unity.

Figure 12 External view of fire simulation in virtual reality model. The smoke is imported by Fire Dynamic Simulation and show a realistic and fluid behavior. For avoiding charging too much the Fire Dynamic Simulator model the window is modelled as a hole and the shading are not modelled at all.

Importing the exodus simulation is important in order to immerse the user in a real exodus scene where other people move around him in search of their exit.

The input file comes from the simulation realized with MassMotion from which it is possible to export an alembic file.

This keeps geometry and animation of the people evacuating but not of the building. Moreover, the little men are represented as identical white standard figures, but the dynamic movement of the walk can be perceived not only as a simple sliding of a static figure, but the avatar reproduces the real movement of the steps and arms.

The import of the .abc file is done as before for the smoke import, through the creation of a timeline to which to associate the alembic object. If different user profiles have been created, they can be exported and imported separately to Unity, so it is possible to manage them more easily if necessary.

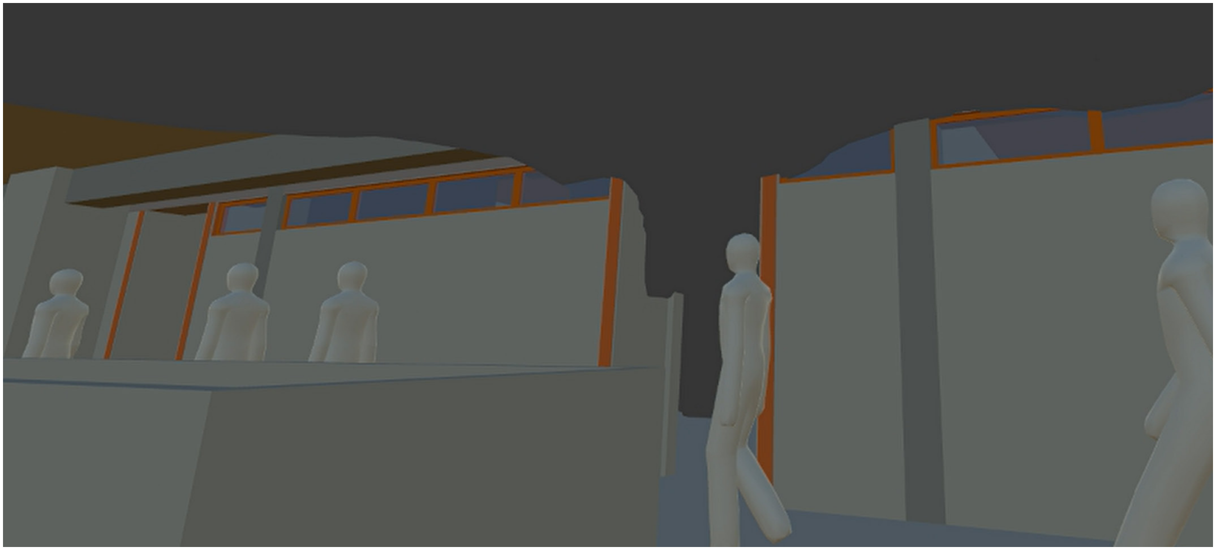


Figure 13 Fire emergency evacuation scenario in virtual reality model. The agent is imported by MassMotion and have a fluid movement. The limit of this visualization is that the agents are simple withe human shape, and this can be a limit to the realism. From the classroom instead it is possible to see the smoke simulation that is starting to propagate in the corridor.

After importing all the different aspect of the simulation, the following step was building a simulation where it was possible to move and interact with the environment.

In some other future work, it will be possible to implement this simulation with some more complex and elaborate rules, but in the context of this thesis the simulation building was limited to add a player inside the structure able to moves and to go to the right exit door.

The platform considered for the integration of the player is the KatWalk VR. This platform allows a 360° movement in the virtual world and must be completed with a virtual reality head-mounted display like HTC Vive.

Much of the structure is built by the framework and the movements are tracked by three sensors, one sensor on the torso for the angle of movement and two to put on the feet for the actual movement.

The main platform is a single body. The space for movement is hollow and it must be moved on it with a movement like skating. The sling is connected to the torso sensor and to the viewer sensor.

The possibility to simulate all the movements, including walking, through the platform can increase the feeling of immersive game and help to make the player feel more involved in the panic situation. However, this technology needs to be improved because the reproduction of movement is non-natural as well as being tiring.

In the use of virtual reality it is also necessary to consider the fact that not everyone is able to use it for a long time because it can cause sickness or dizziness especially if the platform it is not calibrated correctly (head movement and actual movement do not match) and the real movement component in some cases emphasizes this sensation. Besides, with the real movement the player has to do, it can feel the physical fatigue of escaping.

In Figure 14 there is a photo of KatWalk VR while it is used and the prospective from the player point of view.

Figure 14 KAT VR platform, on the left the prospective of the player. The platform allows the player to move in the game with his own body movements. It is sustained by the framework and the foot movement are tracked by two sensors applied on the shoes.

The evaluations and the potentialities in the simulation of these scenarios are multiple and could help to make the performance of a building and its project of exodus better, all for the benefit of the safeguard of the human life due to the possibility to analyze innumerable versions of the same fire in the same building (triggered in different points, on different materials, close to people, far from people), taking into consideration every aspect and every potential danger.

Moreover, evaluations could also be made in the strategic choice of the positioning of the exit routes, besides giving a perspective on the oversizing or under-sizing of the number of exit routes.

Currently, the greatest criticality of this type of application is the ability to dive into the model. For example, the movements of other people who evacuate are determined by paths within the building decided in advance and are not modifiable give the ability to interact with them. Besides, the player can play a role as a user who has to evacuate, but the level of immersion in this type of place, although they offer a 360° view, is still limited by small details that affect the realism.

One is the realism in itself of the simulation, the way to move on the platforms is not completely natural, moreover for example, the hands of the player are visualized like hands of an avatar suspended in the void.

All these small factors carry to not be involved to full in what is being made, but, considering that virtual reality technologies are in development to an exponential speed, it is reasonable to think that in the future all these obstacles could be overcome, offering the possibility of extremely effective scenarios.

CH. 5

CASE STUDY II
THE CITY OF BOLINAS (CALIFORNIA)

Bolinas photo courtesy of Peter Hubbard

DESCRIPTION OF THE CASE STUDY

Bolinas is a community in Marin County, California. It is a census-designated place (CDP) because it is not governed by a legally recognized form of municipal government and is directly subject to county government.

California has several intrinsic characteristics that favor wildfires that are accentuated by the effects of climate change.

The first aspect to consider is the climate. The climate of California has a variable effect depending on the seasons. It is hot and dry in the summer season and leads to a progressive drying of vegetation making the fuel situation very dangerous until the beginning of the rains. This is even more important considering that California is subject to periods of severe drought. In particular, in 2011 began a period of deep drought that lasted until 2017, the worst ever recorded in California. The heavy rains that started in January 2017 have improved the situation and now the state is back to normal.

However, the vegetation is still very much affected by the hard period. There are an estimated 129 million dead trees, and the ground is still very dry. All these trees provide an easy path for the fire to move and spread quickly.

In autumn, however, one of the biggest problems is represented by strong winds coming from the hinterland. They are originated in the inland deserted areas and blowing towards the coast. These winds are called Diablo in northern California and Santa Ana in the south. They are favored by the particular territorial conformation of the state formed by high mountains and valleys that act as a chimney making these winds extremely hot and dry.

These strong offshore winds, due to their very low relative humidity, easily dry the fuels making fires extremely dangerous especially if they occur before the beginning of the winter rainy season. It should be noted that the effects of anthropogenic climate change derive from what could one day be only a minimal amount of warming considering the exponential trend it is manifesting its effects today.

All this factor makes California extremely dangerous in case of wildfire.

The United States Census Bureau uses the term census-designated place (CDP) to distinguish unincorporated places (CDP) from incorporated places (towns, villages).

Bolinas is famous for its solitary character and for not being very open to outsiders. The inhabitants do not intend to make Bolinas a tourist destination. The signs that should lead to the city from State Route 1, which is only two miles away, have been removed by residents many times.

Because of the recurrence of this gesture, the county intervened by voting on the presence of the signs and the residents voted to have signs and preserve their isolated living no longer. The city is at an altitude of 11 m (36 feet) above sea level and is bordered by the Pacific Ocean to the west, the bay (Bolinas Bay) to the south, and the lagoon with the same name, and the island of Kent to the east.

The west coast of the city is a protected area, called the Duxbury Reef State Marine Conservation Area.The area is very important in terms of nature and combines in a small area the lagoon, the bay, and a beautiful coastline.

Bolinas has a warm Mediterranean summer climate (Csb), according to the Köppen-Geiger climate classification system, like most of the Californian coast.

The city center is located on Wharf Road on the eastern side of the city and was built between

1850 and 1920. From an urban point of view, it is not well connected to the nearby cities. Bolinas is 16 Km (10 miles) from San Rafael and 21 Km (13 miles) from San Francisco.

The firefighter's district was built on 14 February 1958, adapting the city to local protection laws. Before the foundation of the structure, some firefighters have been providing services voluntarily since 1954. Today the district not only handles fire protection but also manages emergency medical care and disaster management and serves a fixed population of 2500 people and thousands of tourists and visitors, answering about 250 calls a year. The command consists of a chief, a captain, and a paid firefighter, and 18 volunteers, mostly doctors.

Figure 15 shows the read network around the city of Bolinas. The data are extract from Open Street map.

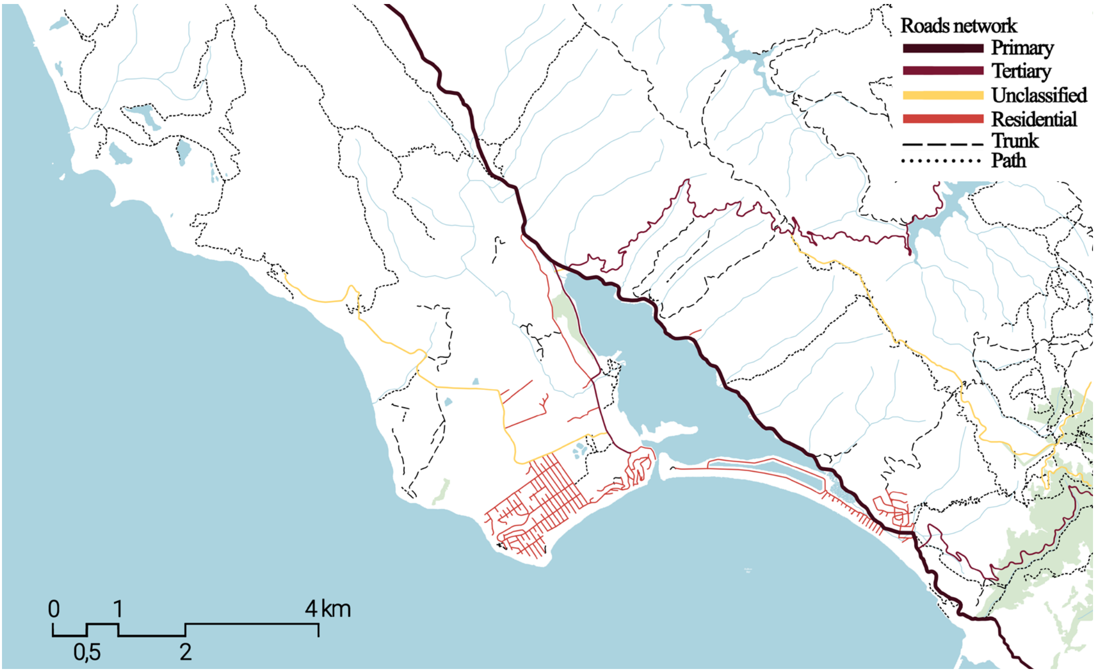


Figure 15 Road network of Bolinas city. In the map it is possible to notice the lack of connection system to the city. Bolinas has been chosen for this research also for this issue because, in case of emergency, if one of the roads is stuck or congested this became a huge problem due to the few alternative routes.

SIMULATION OF WILDFIRE USING FARSITE SOFTWARE

To build the simulation of a fire are necessary a series of data and dedicated software. After having evaluated the various options available for this case it has been opted for the choice of the software FlamMap, using however the simulation model FarSite.

This is because FarSite is able to better adapt to a dynamic scenario at meteorological level (changes of direction and wind speed, humidity, temperature). The various input data have been downloaded from government databases and archives (e.g., LANDFIRE).

The climatic data are taken from nearby weather stations. The Landscape file was created from the LANDFIRE database. On this, however, some problems have emerged related to the size of the ASCII grid, it provides a resolution of the city of Bolinas too low making the whole urban area as class 93 (Urban) despite many of the buildings are made of wood, is full of vegetation and most of the streets are very tight.

In order to simulate a scenario where the fire did not stop only at the edge of the city but also can burn inside it, the urban fuel class has been replaced with a fuel with a moderate load activity Fuel indicate as SB2 (202) (Scott 2005).

However, since it is not suitable because it represents a natural environment, an additional adjustment factor in the. ROS file of 0.5 has been applied, halving the propagation speed even further.

Weather data Regarding the weather scenario, there are two options: a hypothetical scenario with conditions chosen to be favorable to the fire. Obviously, all the chosen inputs are consistent with the location and do not differ from the average Bolinas conditions.

To simulate fires in real days instead it is possible to refer to weather stations. In this case it have been used two, the first Woodacre for the simulation of the scenarios one and two, while the station of Santa Rosa has been used in the simulation of the scenario 3. The weather input of scenarios 1 and 2 have been created through Fire Family Plus.

Fire Family Plus (FF+) is a software that can process weather data recorded from remote automated stations (RAWS). It is a software that has multiple functions that can be grouped into four sub-sets: calculate the NFDRS as well as the Canadian Forest Fire Danger Rating System based on weather and climate data, synthesize climate data to create breakpoints useful for fire management decisions, integration of recording of past fire with historical data to deduce the relationship between the change of the weather conditions and the increase of fires (this information is used to establish fire activity thresholds and monitor fire danger) and as last function it can analyze weather data to estimate the potential and growth of an ongoing fire.

Through this software it was possible to investigate in the data collected by the Woodacre station, writing queries from which emerged days that would have favored the spread of a fire. The parameters used to do the search are the following: Wind speed > = of 10, Wind direction between 345 and 180 (NNO to S directions), and RH 45 mph.

From the days when these events took place were selected those in which the direction of the wind also came from inland and the other characteristics that can influence the propagation of the fire (exposure, relative humidity, moisture fuel content).

Also selected here four events on Fire Family Plus that have been extracted the data for the .FMS file because in that case the file does not require an hourly but daily observation. The selected events are August 13th, 2009, October 3rd, 2009, November 17th, 2014, and May 3rd, 2015. Burning period in scenarios 1 and 2, the duration of the fire is 10 Hours, from 9 am to 7 pm.

For scenario 3, a different LCP file was also used, including a larger area. In this case, since the propagation of fire is no longer of interest in the city, no changes were applied.
The reference weather station is Santa Rosa. For this scenario, the intention was to simulate fire in condition of typical strong wind in California called "diablo wind".
They are originated in the inland deserted areas and blowing towards the coast. These winds are called Diablo in northern California and Santa Ana in the south. They are favored by the particular territorial conformation of the state of California formed by high mountains and valleys that act as a chimney making these winds extremely hot and dry. These strong offshore winds, due to their very low relative humidity, easily dry the fuels making fires extremely dangerous especially if they occur before the beginning of the winter rainy season.
In this case the research for the scenarios was focused on condition with strong wind from the inland on the east and the selected days recorded by the Santa Rosa station are: November 20th, 2004, November 22nd, 2013, October 9th, 2017, and October 27th, 2019.
In scenario three is always ten hours but the time is set according to the time when the wind blows the strongest. The fire model set for run the simulation is Scott and Reinhardt's (2001) in order to consider also crown fire and not only surface fire (like in the model Finney's (1998)). It was enabled also the spotting model and the fire acceleration.

SIMULATION OF WILDFIRE USING WILDLAND FIRE DYNAMIC SIMULATOR SOFTWARE

Creating a Wildland-Urban Interface Fire Dynamics Simulator (WFDS) model, especially if it is large it can be complex to create as it must include spatial geoinformation as well as fuel information.

GMS, Geospatial Measurement Solutions, LLC, has created and made available for free a software useful to create WFDS models, Wildland-Urban Interface Fire Dynamics Simulator (WFDS) Input File Creator.

GMS is a company specialized in software engineering, database design and development, spatial analysis, and image processing for the environmental, public services, and telecommunications sectors. GMS offers services in the application of GIS solutions (mobile and desktop), software, and databases to meet the business needs of our customers.

The Wildland-Urban Interface Fire Dynamics Simulator (WFDS) Input File Creator is developed in Java language to create input files from GIS datasets. The key features of the application are at first creation and visualization of Wildland-Urban Interface Fire Dynamics Simulator input files dependent on geospatial data.

Numerous geospatial data formats can be read and transformed by Wildland-Urban Interface (WUI) Fire Dynamics Simulator, loading and visualization of spatial inputs representing soil, barriers, surface fuels, trees, buildings, and domains.

But it is also able to create and locate spatial inputs representing soil, barriers, surface fuels,

But it is also able to create and locate spatial inputs representing soil, barriers, surface fuels, trees, buildings, and domains.
Some other feature of the software are resampling of geospatial input data, the visualization of raw LIDAR point clouds in 2-D, 3-D mode, the visualization of Wildland-Urban Interface (WUI) Fire Dynamics Simulator simulation outputs, and the creation of cross-sectional views of the GIS data.
Geospatial data are data associated with explicit information about geographic positioning and can be divided into different types:: vector data represent elements using points, lines, or polygons. The vertices can have both horizontal and vertical extension of the element.
Examples of fire model inputs that could be stored as vector data are: building footprints (polygon drawing the boundary), fuel surfaces described as polygons whose area is the surface of the fuel, ignition points described as polygons points or lines, trees described as points to which the element attributes are associated (height, width, type of tree), and model domains.
A raster image is a two-dimensional grid organized in a metric of rows and columns.
Every cell of the grate has a value that represents a particular value that describes that cell in the context of the raster and of what it represents (in the raster of the elevation every cell contains the value of the elevation).
Examples of the raster are: elevation, pixel contains a numerical value with the elevation, fuel, each pixel represents a particular surface fuel, trees, each pixel can contain data such as crown height, density, and building heights. Both, raster, and vector data, can be associated or sometimes related tabular data.
Most vector inputs have a set of associated attribute tables but also some raster data can have an associated table that gives additional information for each pixel.
The aim of this type of simulation was finding a way to recreate the fire in a three-dimensional way despite the size of the area to be simulated which is very large.

The base file was created with the Wildland-Urban Interface (WUI) Fire Dynamics Simulator (WFDS) Input File Creator software. The first attempt was to create the model with the Fuel Model base.

The main problem with this approach, however, was the fact that it is very difficult to establish the environmental conditions identical to those included in the simulation on FarSite as well as giving the right properties to the different fuel classes.

For this reason, in the end, it was possible to obtain a fire similar to the other simulation one but in any case, different and not suitable for integration into the 3D visualization with the other elements that make up the final simulation.

The second attempt was to use as the basis of the model no longer the fuel model but the Rate of spread output (ROS) of the fire already simulated on FarSite. This file creates a map that uses a color scale to represent the speed of fire propagation expressed as a unit of surface area relative to the unit of time (meters per second or chains per hour).

The map can then be exported as a .tif image, thus preserving all the information with which it is associated, and imported in the application for create the simulation input.

The file created with Wildland-Urban Interface Fire Dynamics Simulator has been created using has input elevation, domain, ignition point and rate of spread output.

The software obviously does not have the option to process the rate of spread, so the file has been inserted as fuel model that has as input a .tif file with the same characteristics. The software then associates to each cell a speed class among those present in the input.

For the building the cell size was too big for the dimension of single small building as they are in Bolinas. Since the software optimizes each cell to a uniform condition, the result were entire cells indicated as buildings much larger than the individual building and cells without buildings, the result was far from reality so it was overlooked. The same thing happened for the street system.

Figure 16 show the comparison with the fire simulation and the rate of spread output.

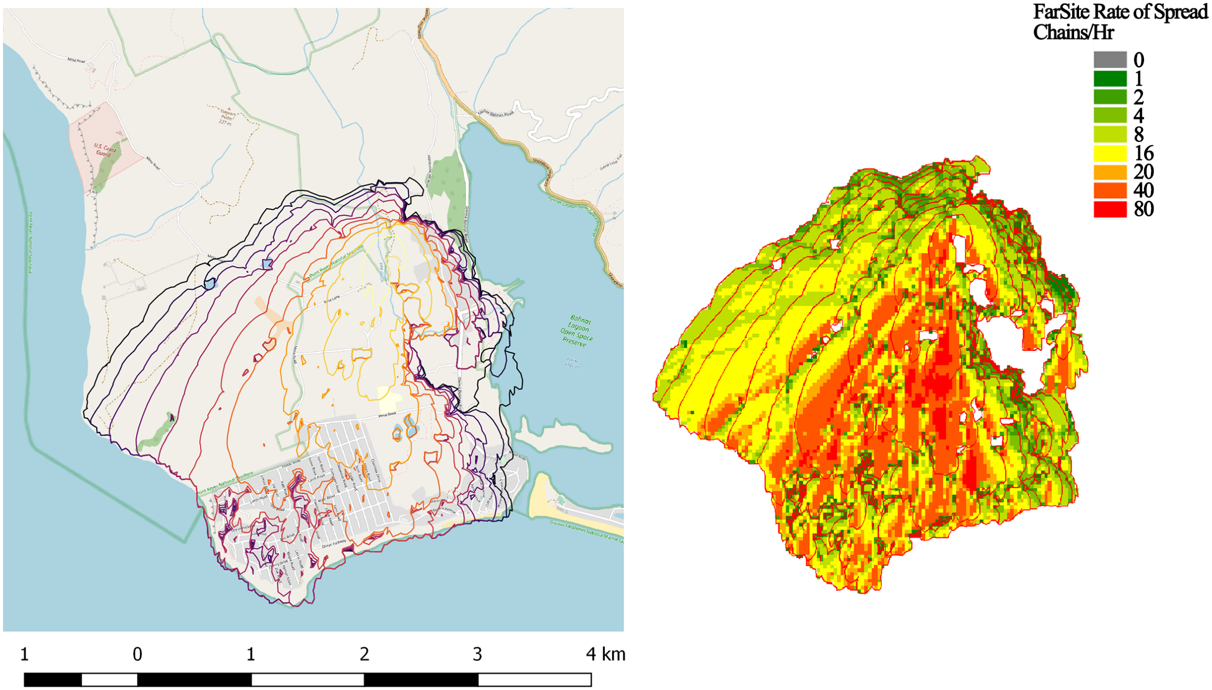


Figure 16 Rate of spread output from FarSite related to a simulation of scenario 1. The two images are different output of the same simulation. The fire spread is calculated for 10 hours and the lines in both the images indicate one-hour timestep.

Using this basis, each speed category was assigned a burning time deduced from the rate of spread, Farsite output where each color is associated with the burning speed.

Considering the area of the cells of the Rate of Spread output and the area of the cells of Wildland-Urban Interface Fire Dynamics Simulator to each Rate of Spread class has been associated a RAMP function in the code. RAMP is an option in Fire Dynamics Simulator that can set a function in relation to time. In the time of the RAMP must be considered as second zero the moment in the simulation when that cell get ignited.

With this option to each Rate of Spread class has been assigned the time before the ignition of the fire (the time necessary to fuel to be dry), the time when the fuel is on fire, and the time of the decay phase.

Then, to have a realistic display of the smoke propagation, in the code have been specified the feature of the wind like direction and speed. In this way, a very plausible visualization was obtained. The terrain has been processed with the Wildland-Urban Interface (WUI) Fire Dynamics Simulator (WFDS) Input File Creator software using the Digital Elevation Model (DEM).

Figure 17 show the portion of terrain included in the simulation

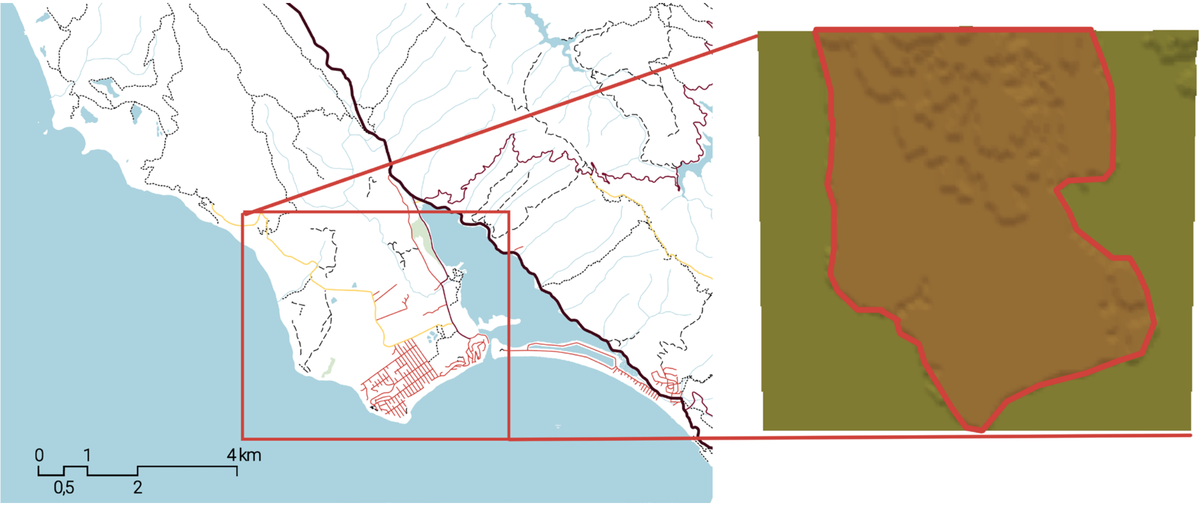


Figure 17 View of the peninsula of Bolinas with the fire simulation, the image B is the top view of the terrain recreated in Wildland-Urban Interface Fire Dynamics Simulator

The fire simulations have been run for ten hours for all the three scenarios around Bolinas. The main aim it was recreate in Wildland-Urban Interface Fire Dynamics Simulator the simulations run with Farsite that have been integrated with other simulation. This means that the important part was having two fire simulation as similar as possible and not compare the semi empirical model with the physical one.

Figure 18 show the evolution of fire for the scenario 1, ignition point 3.

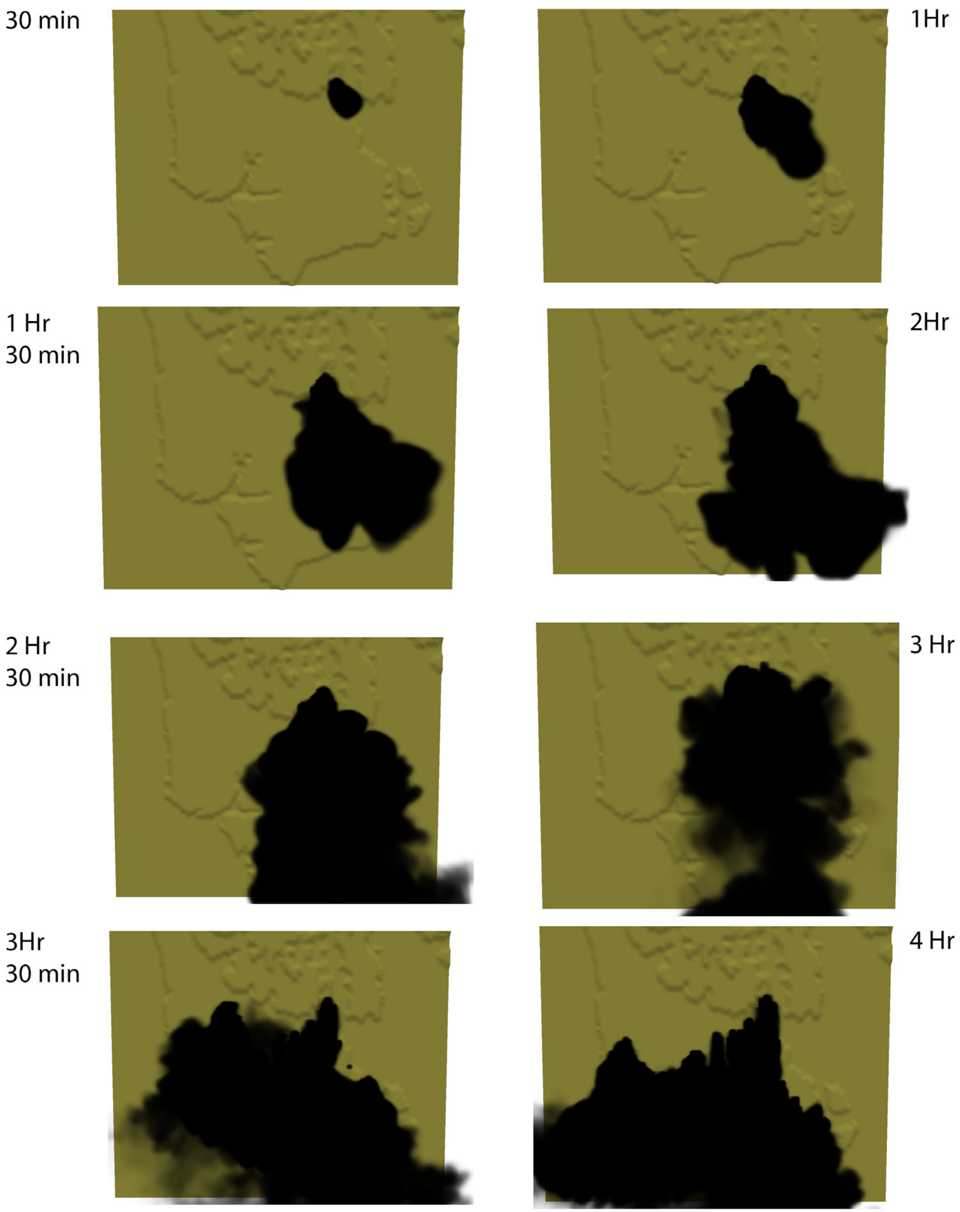


Figure 18 Wildfire simulation in Wildland-Urban Interface Fire Dynamics Simulator that replicate the simulation in hypothetical condition for the ignition point 3.

ANALYSIS OF SCENARIOS AND RESULTS

Since the simulation must be integrated and must communicate with other simulations (traffic and telecommunications) three scenarios have been chosen in order to put the city of Bolinas in three different emergency situations.

Scenario 1 is a small fire in a three-mile radius area around Bolinas. There are considered three different ignition points placed in strategic places to expose the town to the fire in a different direction. One is on the West Side, another on the East Side and the last one is on the north near to the main escape road.

Scenario 2 is a medium fire within a 15-mile radius of Bolinas, with increasing speed. This fire is bigger and burns for more time than the first one. The two ignition points are the first one near to the main road but more on the north and far from Bolinas instead the second here is more distance between the point and the main road but is more on the South and, so, closer to Bolinas.

Scenario 3 is a large fire within a 25-miles radius of Bolinas. The fire is feed by strong and dry winds in direction east to west. The huge fire starts in an area around Petaluma so all the firefighter resources are involved in that huge fire, but a small fire could start near Bolinas that also need to evacuate. The fire simulated in this scenario is powered by a Diablo wind, so its propagation is very fast and very violent. The two ignition points for the huge fire are both near the two highways.

Figure 19 summarizes in three maps the three scenarios

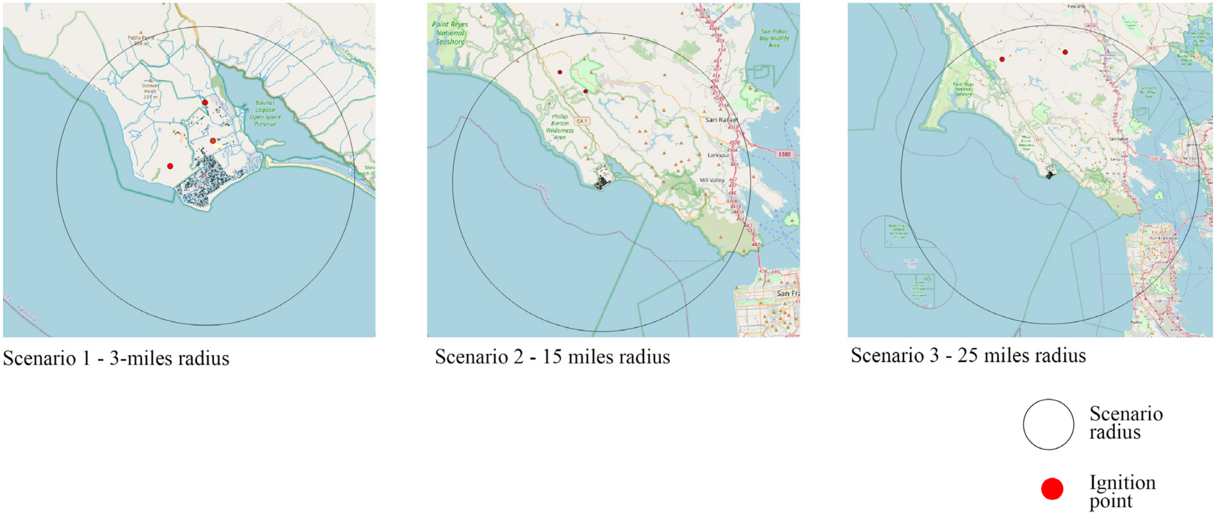


Figure 19 Summary of scenarios of wildfire simulation. Scenarios areas has been defined by three different radius around Bolinas in order to create different situation to handle in case of evacuation. With the same propose have been chose the ignition point of the fire that are aimed to close different escape routes creating different evacuation scenarios

For Scenario 1 and Scenario 2 have been run simulations for four days. For each day three ignition points. In addition, there is a simulation that is not referred to an event in the past of Bolinas but are some hypothetical characteristic (selected based on the real average data of the area) that can influence the spread of the fire in direction of the town with a medium speed.

Figure 20 reports two scenarios, the hypothetical one and the one with the condition of October 3rd, 2009.

The hypothetical chosen are: Simulation time (9:00 AM - 7:00 PM), Relative humidity (15%), Wind Speed (15-18 Mph), Wind direction (NNE), Cloud Cover (0%), Temperature (65 °F).

Instead the October 3rd, 2009 condition recorded by Woodacre station are Simulation time (9:00 AM - 7:00 PM), Relative humidity (45%), Wind Speed (18-20 Mph), Wind direction (NW), Cloud Cover (0%), Temperature (62 °F).

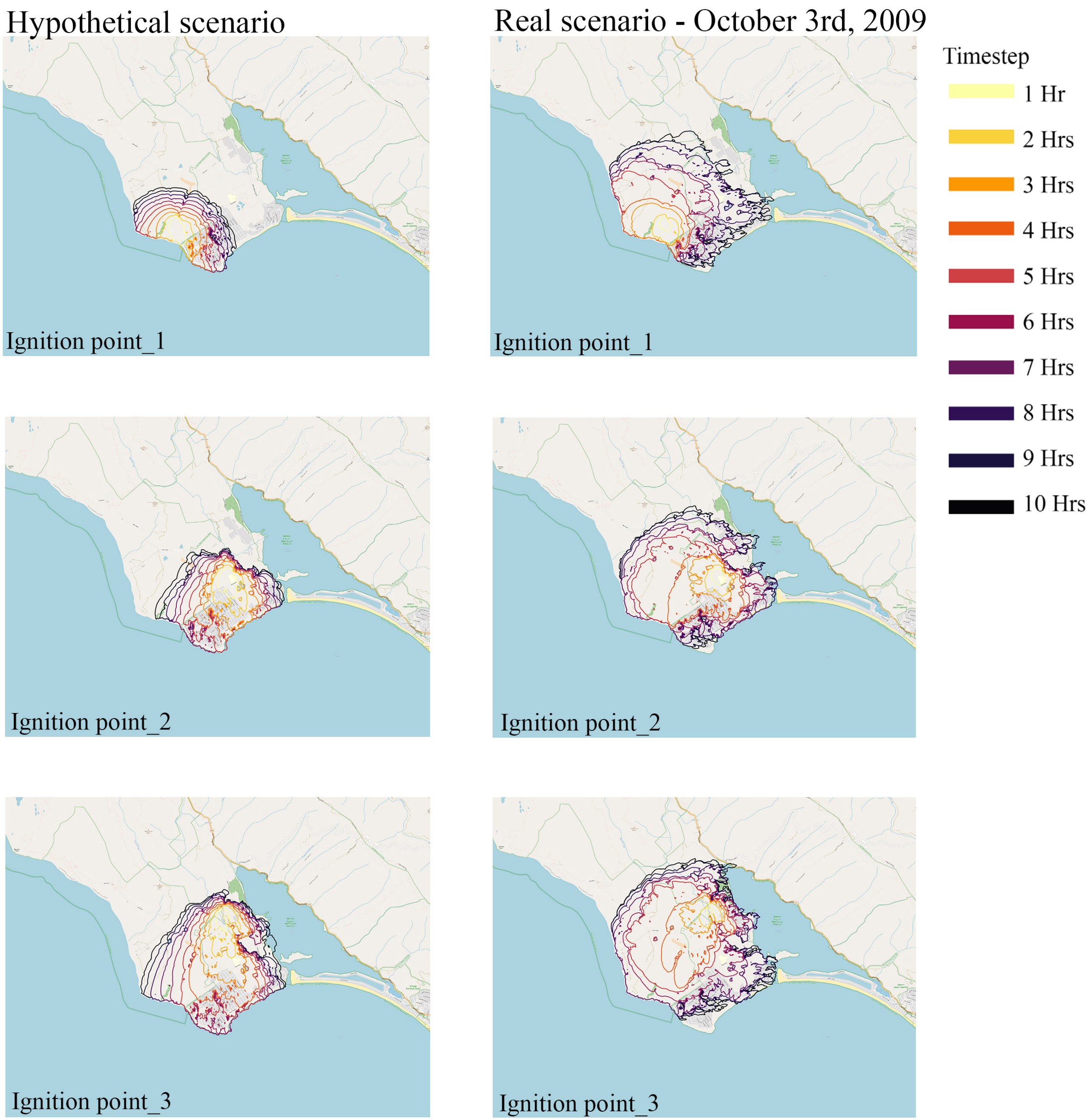


Figure 20 First scenario simulations in hypothetical condition and real condition. The different color of the line indicates the fire line for each timestep

In the first simulation is evident how the position of the ignition point can influence the entity of the fire, in ignition point one in fact the fire in ten hours arrive and it burn half of the city, instead of with ignition point 3, in the same period and with the same condition the area burned is the whole any a larger space around it.

Another aspect to put in evidence is that with ignition point 2 after one hour the fire is already touching Bolinas, instead of with ignition point 3 this happens after three hours.

This means that in scenario three people have also more time for leaving the houses an escape.

In real scenario conditions due to the different wind direction, the burned area is a bit different, it is bigger than the first scenario but also after ten hours not all, the city gets burned as happens in the first scenario.

The reason why has been chosen the scenario of October 3rd, 2009 is also because it is interesting to underline how the spreading is much more than the hypothetical condition scenario, which has been selected for being the best features for the fire spreading according to average in Bolinas.

The different spread of fire is due mainly to different wind directions, in the real scenario the fire is driven to a different fuel type (near the coast) where it can spread extremely fast, as it is possible to in the 5th timestep.

In the following tables are reported some specific results for each scenario. Table 8 reports data of the hypothetical scenario, instead Table 9 report the data of October 3rd, 2009. The data reported for each one hour timestep are:

1. Total acres: Number of acres burnt from the second 0 to the timestep considered
2. Timestep Acres: Number of acres only in the considered timestep
3. Fire: Number of active fires in the considered timesteps. The presence of multiple fire is due to the spotting phenomenon.
4. Buildings: Total number of building involved in fire from the first timestep to the considered one

Table 8. Data of the fire simulated in hypothetical condition, scenario 1

	1Hr	2Hrs	3Hrs	4Hrs	5Hrs	6Hrs	7Hrs	8Hrs	9Hrs	10Hrs
Hypothetical scenario | Ignition Point 1										
Total Acres	54.69	128.33	221.87	323.42	424.90	544.80	661.92	777.20	866.51	940.87
Timestep Acres	54.69	73.64	93.55	101.55	101.48	119.90	117.11	115.28	89.31	74.36
Fires	0	1	5	8	6	6	7	13	11	8
Buildings	1	23	95	172	232	395	511	652	770	898
Hypothetical scenario | Ignition Point 2										
Total Acres	65.22	210.59	410.79	586.73	784.07	968.92	1085.98	1183.98	1264.09	1364.20
Timestep Acres	65.22	145.37	200.20	175.94	197.34	184.85	117.05	98.01	80.11	100.10
Fires	0	5	16	19	19	21	23	16	12	14
Buildings	45	373	714	967	1121	1293	1387	1447	1502	1516
Hypothetical scenario | Ignition Point 3										
Total Acres	32.94	204.43	516.40	890.07	1203.82	1537.34	1729.55	1895.42	2040.44	2247.32
Timestep Acres	32.94	171.49	311.96	373.68	313.75	333.52	192.21	165.86	145.02	206.88
Fires	1	8	17	28	22	40	34	36	24	26
Buildings	17	72	415	862	1129	1436	1519	1612	1668	1734

Table 9. Data of the fire simulated in real condition the day October 3rd, 2009, scenario 1

	1Hr	2Hrs	3Hrs	4Hrs	5Hrs	6Hrs	7Hrs	8Hrs	9Hrs	10Hrs
October 3rd, 2009 | Ignition Point 1										
Total Acres	20.89	99.00	274.16	412.71	728.86	1097.86	1258.80	1771.11	2082.39	2244.21
Timestep Acres	20.89	78.11	175.15	138.55	316.16	369.00	160.94	512.31	311.28	161.82
Fires	1	2	3	3	9	15	21	46	50	52
Buildings	0	4	8	79	113	359	606	979	1330	1481
October 3rd, 2009 | Ignition Point 2										
Total Acres	28.61	96.20	235.08	635.70	1268.82	1602.23	1909.03	2217.12	2369.25	2439.10
Timestep Acres	28.61	67.59	138.88	400.62	633.12	333.40	306.80	308.09	152.13	69.85
Fires	1	1	5	22	42	30	34	40	52	43
Buildings	8	43	168	575	768	999	1333	1575	1678	1726
October 3rd, 2009 | Ignition Point 3										
Total Acres	6.41	56.57	180.97	647.95	1339.89	1816.18	2303.53	2633.92	2843.68	3006.58
Timestep Acres	6.41	50.17	124.40	466.98	691.94	476.29	487.36	330.39	209.76	162.90
Fires	1	2	6	18	24	40	49	62	60	70
Buildings	5	21	67	162	232	488	885	1151	1406	1614

Scenario 2 is a medium fire not so far from Bolinas ignited near the main roads used by people for evacuating. In this case there are only two ignition points and the results reported are of the big fire, the small fire near Bolinas is not considered.

In the main time a small fire start in the neighborhood of the city forcing people to leave as is possible to see in Figure 21.

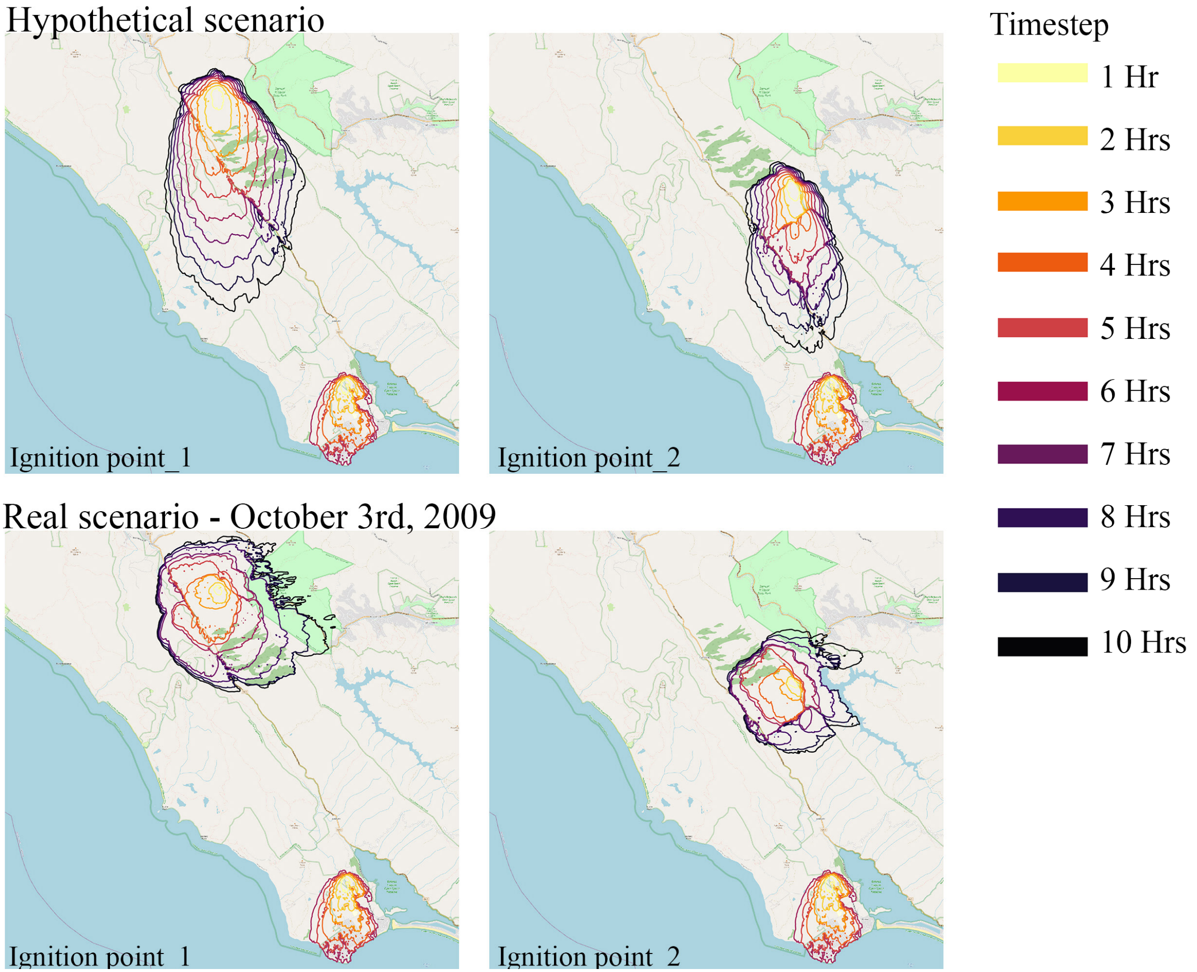


Figure 22 Scenario 3 simulations in condition of “diablo wind”. The different color of the line indicates the fire line for each timestep

This situation is really dangerous because the big fire, in this case, is in a forest, so it is a crown fire (the fire has a veritcal component of spreading, and it is expanding through the tree's canopy); instead in the scenario one the fire was basically a surface fire.

The fire take time to cross such a big road like the highway Route State 1, this means that the road will be stopped by fire for few hours before the fire front moving. The Route State 1 is the only big roads connected to Bolinas so this type of fire can heavily limit the possibility of the inhabitants to escape. In the tables are reported some specific results for the scenario. The Table 10 report data of the hypothetical scenario, instead Table 12 report the data of the October 3rd, 2009. The type of data reported are the same of the tables for scenario 1.

Table 10 Data of the fire simulated in hypothetical condition, scenario 2

	1Hr	2Hrs	3Hrs	4Hrs	5Hrs	6Hrs	7Hrs	8Hrs	9Hrs	10Hrs
Hypothetical scenario | Ignition Point 1										
Total Acres	75.17	388.74	899.87	1551.14	2458.95	3509.73	4635.56	5971.47	7357.22	8752.56
Timestep Acres	75.17	313.57	511.13	651.27	907.81	1050.78	1125.83	1335.91	1385.75	1393.34
Fires	2	3	14	19	23	26	19	21	21	24
Buildings	0	0	19	34	46	46	46	46	47	52
Hypothetical scenario | Ignition Point 2										
Total Acres	63.95	197.68	336.70	576.89	1039.86	1632.62	2149.16	3006.62	4035.11	5186.80
Timestep Acres	63.95	133.74	139.06	240.19	462.97	592.77	516.53	857.46	1028.49	1151.69
Fires	2	1	8	6	10	13	13	36	46	45
Buildings	0	0	0	0	0	0	5	9	21	73

Table 11 Data of the fire simulated in real condition the day October 3rd, 2009, scenario 2

	1Hr	2Hrs	3Hrs	4Hrs	5Hrs	6Hrs	7Hrs	8Hrs	9Hrs	10Hrs
October 3rd, 2009 | Ignition Point 1										
Total Acres	19.32	104.07	321.18	932.33	1596.68	2455.35	3771.65	4990.95	6108.72	6810.81
Timestep Acres	19.32	84.75	217.11	611.15	664.35	858.67	1316.30	1219.31	1117.77	702.09
Fires	1	2	9	13	20	26	33	38	43	57
Buildings	0	0	0	10	22	27	35	53	64	68
October 3rd, 2009 | Ignition Point 2										
Total Acres	20.62	66.65	188.13	607.20	1101.09	1488.88	2001.32	2731.28	3454.66	4015.36
Timestep Acres	20.62	46.03	121.48	419.07	493.89	387.79	512.44	729.95	723.30	560.70
Fires	1	2	2	4	8	6	10	22	27	38
Buildings	0	0	0	0	0	0	1	2	4	40

For the scenario three have been run simulations for four days. The condition chosen for this scenario are suitable to meteorological event that in California are called Diablo wind, extremely hot and dry. This type of wind can influence the propagation of fire a lot, and most of the dangerous wildfire happened in California were on the influence of this wind. The fire start near the city of Petaluma and the four days selected to represent this scenario are: November 20th, 2004, November 22nd, 2013, October 9th, 2017, October 27th, 2019.
Figure 22 show two scenarios, November 20th, 2004 and the one with the condition of November 22nd, 2013.

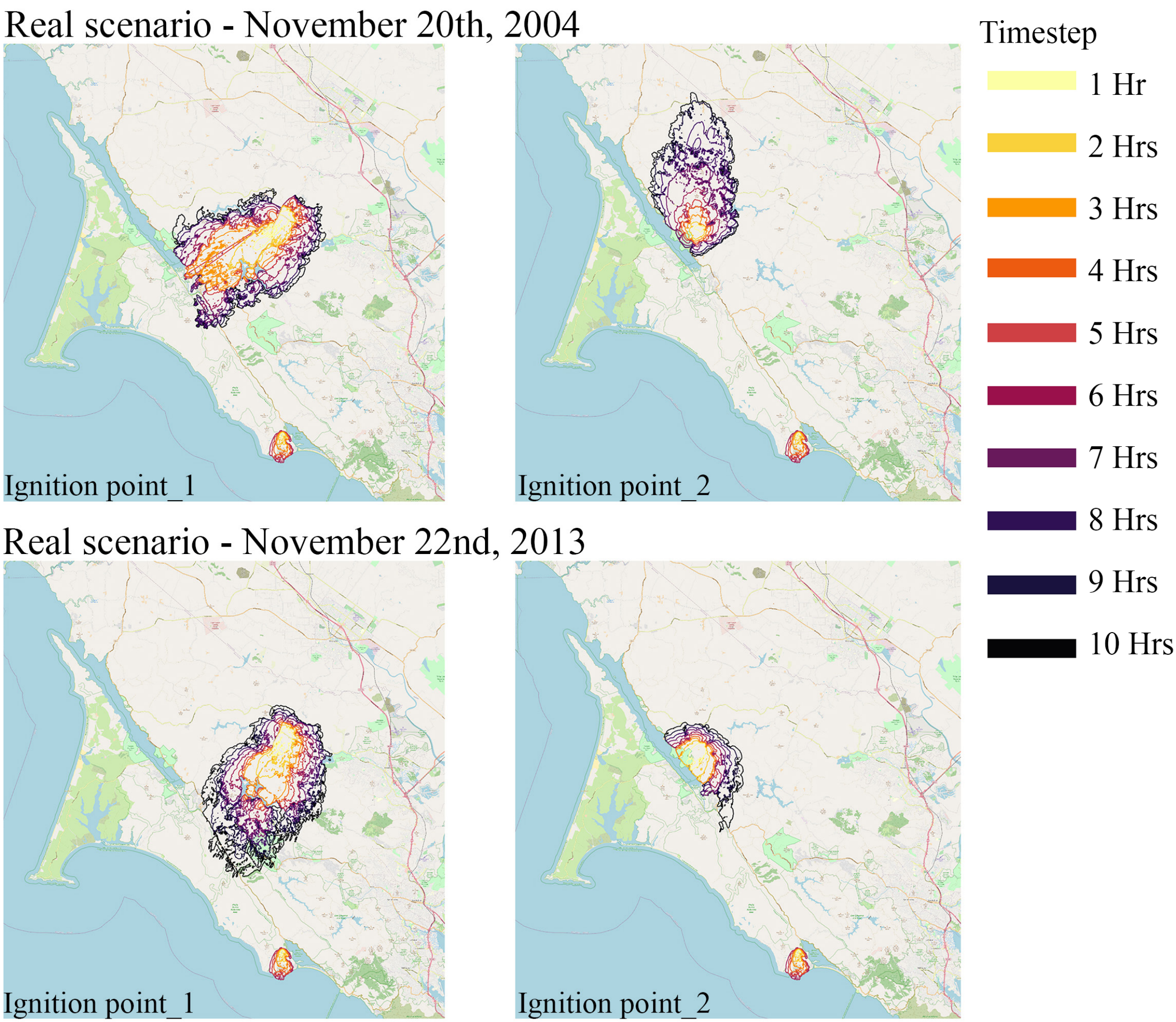


Figure 22 Scenario 3 simulations in condition of "diablo wind". The different color of the line indicates the fire line for each timestep

Also in this scenario have been simulated a small fire around Bolinas in order to consider the urgency of evacuate the city when a big fire is expanding and most of the fire fighter resources are involved on it. So the fire near Bolinas becomes harder to contain due to the lack of resources and the priority given to the huge fire.

The research for those days in the past have been made mainly selecting particular wind condition. The filters applied were the wind speed more than 40 Mph and the direction from the inland.

About the two cases reported for November 20th, 2004 the condition recorded by Santa Rosa station are: Simulation time (10:00 AM - 8:00 PM), Relative humidity (20%), Wind Speed (Max 46 Mph), Wind direction (SW), Cloud Cover (0%), and Temperature (65 °F).

Instead the November 22nd, 2013 condition recorded by the same station are: Simulation time (10:00 AM - 8:00 PM), Relative humidity (8%), Wind Speed (Max 47 Mph), Wind direction (NE), Cloud Cover (0%), and Temperature (62 °F)

Table 12 Data of the fire simulated in real condition the day November 20th, 2004, scenario 3

	1Hr	2Hrs	3Hrs	4Hrs	5Hrs	6Hrs	7Hrs	8Hrs	9Hrs	10Hrs
November 20th, 2004 | Ignition Point 1										
Total Acres	115.1	562.4	1090.7	1994.9	3133.77	4408.34	9949.45	18485.4	22963.8	24875.8
Timestep Acres	115.1	447.3	528.28	904.20	1138.79	1274.57	5541.11	8535.97	4478.45	1911.93
Fires	1	3	16	20	41	58	231	391	445	408
Buildings	0	4	11	51	88	106	495	877	957	996
November 20th, 2004 | Ignition Point 2										
Total Acres	121.8	550.2	1074.0	1972.4	2902.81	5057.47	11364.3	19860.6	26352.9	28933.3
Timestep Acres	121.8	428.3	523.75	898.44	930.35	2154.66	6306.88	8496.31	6492.33	2580.34
Fires	1	1	6	5	17	26	209	419	384	322
Buildings	0	3	5	25	62	79	186	294	460	516

Table 13 Data of the fire simulated in real condition the day November 22nd, 2013, scenario 3

	1Hr	2Hrs	3Hrs	4Hrs	5Hrs	6Hrs	7Hrs	8Hrs	9Hrs	10Hrs
November 22nd, 2013 | Ignition Point 1										
Total Acres	986.8	3290.	7144.88	8303.45	9920.52	13406.13	18700.95	22930.47	30306.76	41141.
Timestep Acres	986.8	2303.	3854.59	1158.56	1617.07	3485.61	5294.82	4229.52	7376.29	10834.
Fires	37	112	171	110	96	140	305	329	615	1102
Buildings	4	37	116	135	167	248	352	495	669	985
November 22nd, 2013 | Ignition Point 2										
Total Acres	861.1	2064.	3117.62	3413.64	3798.70	4748.38	5976.31	7133.25	9183.42	11698.
Timestep Acres	861.1	1203.	1053.08	296.02	385.06	949.68	1227.94	1156.94	2050.17	2515.3
Fires	24	51	41	31	30	38	50	62	112	178
Buildings	1	31	71	73	75	103	170	195	265	371

This scenario has been chosen for simulate a catastrophic situation of fire, in fact, if compared with scenario one and two, the simulation of scenario three is way more extended, moreover the area is surrounded by forests and trees so the intensity of flames is really high. Diablo winds are a huge problem in case of fire because they can drive violent wildfire events.

In the following tables are reported some specific results for the scenario. Table 12 report the November 20th, 2004 data, instead report the data of the November 22nd, 2013. The type of data reported are the same of the tables for previous scenarios.

In this case there are only two ignition points and the results reported are of the big fire, the small fire near Bolinas is not considered.

INTEGRATION OF FIRE SCENARIO WITH OTHER SIMULATIONS IN UNITY3D SOFTWARE

The research developed in Berkeley with the case study of Bolinas is a collaborative work that try to put together multiple domains (fire, communication, and traffic).

The workflow of the research consists of three steps: the first one is fire spread simulation depending on real meteorological data and vegetation; the second step is the communication simulation and the last one is the dynamic traffic modelling.

The purpose of the integrated simulation is to investigate the interdependencies between the fire simulation, the traffic and the communication networks in an interdisciplinary way, in order to determine the performance lmits for them in evacuation strategies under the dangerous conditions of wildfire.

To evaluate the interdependence, one of the objectives is to develop a simulation in the Unity 3D software. The simulation consists in the evacuation by car in wildfire scenario. In the simulation the players must evacuate from Bolinas by car.

Players have different visualization and, according to their perception of danger while they are driving, they have to move and make decisions.

The game must be played by the inhabitants of Bolinas, to record their choice driven also by local knowledge. The Unity simulation must be integrated with all the simulation: fire, traffic, and communication.

Integrate the simulation of smoke with Unity is not immediate because Smokeview is a viewer, while Unity needs three-dimensional input.

However, it is possible through Fire Dynamics Simulator to create plot3d files in relation to time, processing different values (density, velocity, pressure…).

Considering the size and the length of the simulation, ten hours, it was difficult to manage the creation of a frame each second. For this reason, it was decided to create a frame every 20 seconds.

This has affected a little bit the fluidity of the result, but it significantly lightened the work. The file is then imported into the Paraview analysis software and read in relation to a file (.xyz) also produced by Fire Dynamics Simulator. Once they were imported, they were displayed as isosurfaces using the density value as a reference value for creating the contour. In this way, the same animation of Smokeview has been recreated on the Paraview software, but by a surface defined by a mesh.

Using density as parameter, it is possible to ask the software to process a surface that follows the same shape as the smoke.

Once the animated mesh has been processed, it can be exported as a series of .obj files. The latter can be imported into the three-dimensional modeling software Blender and merged into a single animation compatible with Unity.

Due to the number of frames for this simulation, the animation has been divided into four parts.

In Unity, everything gets put together through the organization of a timeline.

First, the alembic files have to be imported through a specific plugin in the timeline as an alembic shoot asset.

Then it is important to associate each part to a time of visibility in the game, in this way the sequence is guaranteed without seeing at the same time all the four parts of the animation. The two options for each part of the animation must match for a good effect.

Figure 23 show the smoke simulation imported in the Unity Game.

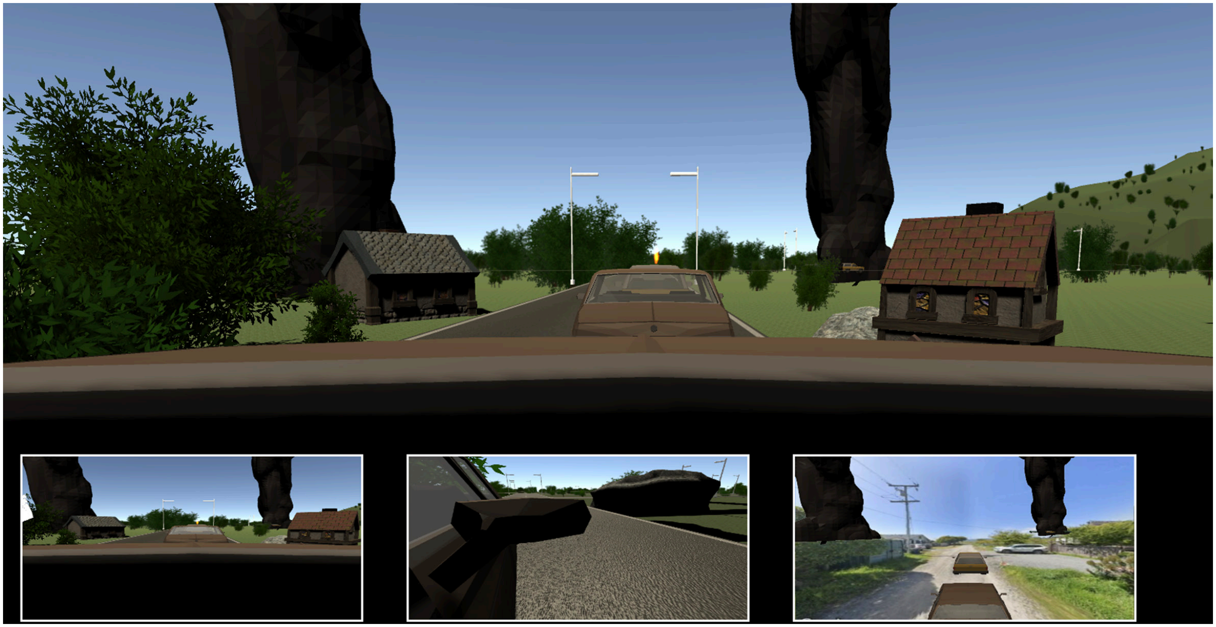


Figure 23 Evacuation simulation developed for the city of Bolinas, in this frame it is possible to see the smoke simulation from integrated. Image from the unity simulation developed with Kenichi Soga, Louise K. Comfort, Yanglan Wang and Kecheng Chen

The communication network is related to traffic simulation. The aim of this type of simulation is evaluate the capacity of community organizations and residents to mobilize collective action under the danger of wildfire, and the gaps between plans and real-time operating conditions.

The traffic simulation is aimed to understand queuing and congestion phenomenon. It is also related to the fire, in fact when the fire arrives near a road for a while that part of the roads network became non practicable by car.

But this is just a temporary issue because when the fireline moves than that roads becomes practicable again. For analyzing this issue in the evacuation system traffic simulation has been integrated with the fire time step and the flame length output.

If the fire that is interrupting the road is a surface fire (grass), it is not so dangerous as crown fire, and car could cross that roads also if in that moment it is burning. All the aspects of this research program have been integrated and influenced by the other simulation.

The attempt of this interdisciplinary research is to understand how much a simulation can influence the others in function of an improvement and greater precision. Such complex phenomena as the evacuation of an entire city cannot be simplified to single results of divided analysis but must be integrated to have a result close to how the facts could really happen in an emergency situation.

CONCLUSION

The importance of fire emergency simulation in Fire Safety Engineering is indispensable.
In this work, a multiscale methodology using Fire Dynamic Simulator and virtual reality model is provided as a tool for simulating fire emergency scenarios, highlighting how such simulations can help to prepare evacuation strategies and to study human behaviors in emergency conditions. The methodology integrates results from computational fluid dynamics software into a virtual environment.
Virtual reality is becoming an increasingly effective tool in training in emergency situations, building management, and lifesaving. It is therefore important to support the construction of more comprehensive and realistic scenarios.
To show the applicability of the methodology, two scenarios are introduced at different scales. In the first case scenario, the simulation of the fire has been successful developed in a building school placed in Melzo (Milan) by integrating inputs derived from different simulations into Unity 3D software.
The virtual reality scenario developed in this thesis is able to simulate a fire emergency scenario and to conduct emergency drillings in a safe and cheap way. This makes it easier to evaluate the evacuation performance of the building.
The fire drill simulation proposed is more complete than what is proposed in the literature so far as it is able to implement also the smoke imported directly from a fluid dynamic software

contributes creating an immersive scenario where the player can move.

The reduced visibility due to the real propagation of the smoke imported within the model it is a powerful tool for evaluating difficulties in the evacuation system in relation to different fire scenarios.

Having the possibility to build customized condition for fire scenario and evacuation in the virtual reality environment it is an important option for evaluating the building in all the possible case of a fire emergency, also in the worse one.

The second case scenario was developed by the University of Berkeley (CA), and it focuses on the city of Bolinas. The simulation of a fire scenario at the urban level in virtual reality combining telecommunication networks, traffic, and the fire is a new idea in the field of Fire Safety Engineering. Fire simulation has been developed by using the Wildland Urban Interface Fire Dynamics Simulator.

The simulation has been realized using as an input the rate of spread (ROS) output from FarSite and proposes a simpler and lighter alternative in terms of calculation than the classic use of the software. Moreover, the main scope of the simulation was to import it in virtual reality and to be integrated with the vector data obtained from FarSite. Despite it is not the most classic way to proceed, it gave the possibility to obtain a realistic visualization of the fire scenario in a very large area.

The realistic propagation of smoke and its visualization in Unity 3D software is fundamental for creating an immersive scenario and evaluating the decisions of users in the function of the perception they have of the danger of the fire and smoke.

In fact, in Wildland Urban Interface Fire Dynamics Simulator it is possible to simulate the fire as a dynamic object including its realistic spreading. Such simulation would be not possible with a particle system provided by Unity 3D software where fire and smoke are generated from a static point.

The proposed applications, therefore, show how to create an immersive virtual reality scenario close to real emergency conditions by including fire, evacuation process, smoke, and virtual environment.

The presented model is simple because it just includes the movement of the player, but it can be further improved with the planning of more complex action inside the simulation, with specific rules and tasks.

Further research will focus on the development of fire scenario simulations aiming at verifying the placement of emergency signals and how the smoke can influence their visibility. Moreover, the research will be oriented towards the study of physical and psychological human parameters during the simulations of emergency scenarios to evaluate the escape routes and the exodus model. Test scenario for employees in complex facilities such as shopping centers, hospitals, stadiums, and trade shows will be taking into account to train them in case of an emergency event.

REFERENCES

An, A. Y., Ryu, E. M., and Kim, H. S. (2014). "Investigations on structural safety of office room based on fire simulation and transient heat transfer analysis." *World Journal of Engineering and Technology,* 2(3), 20-26.

Anderson, H. E. (1981). *Aids to determining fuel models for estimating fire behavior, US* Department of Agriculture, Forest Service, Intermountain Forest and Range

Argasiński, J. K., Węgrzyn, P., and Strojny, P. "Affective VR serious game for firefighter training." *Proc., Workshop on affective computing and context awareness in ambient intelligence,* 43.

Backlund, P., Engström, H., Gustavsson, M., Johannesson, M., Lebram, M., and Sjörs, E. (2009). "SIDH: a game-based architecture for a training simulator." *International Journal of Computer Games Technology,* 2009.

Burigat, S., and Chittaro, L. (2016). "Passive and active navigation of virtual environments vs. traditional printed evacuation maps: a comparative evaluation in the aviation domain." *International Journal of Human-Computer Studies,* 87, 92-105.

Castle, D., Mell, W. E., and Miller, F. J. (2013). "Examination of the Wildland-Urban Interface Fire Dynamics Simulator in Modeling of Laboratory-Scale Surface-to-Crown Fire Transition."

Cha, M., Han, S., Lee, J., and Choi, B. (2012). "A virtual reality based fire training simulator integrated with fire dynamics data." *Fire Safety Journal*, 50, 12-24.

Chittaro, L. (2015). "Designing serious games for safety education:"Learn to brace" versus traditional pictorials for aircraft passengers." *IEEE transactions on visualization and computer graphics,* 22(5), 1527-1539.

Chittaro, L., Corbett, C. L., McLean, G., and Zangrando, N. (2018). "Safety knowledge transfer through mobile virtual reality: A study of aviation life preserver donning." *Safety science,* 102, 159-168.

Chittaro, L., and Ranon, R. "Serious games for training occupants of a building in personal fire safety skills." *Proc., 2009 Conference in Games and Virtual Worlds for Serious Applications,* IEEE, 76-83.

Cuesta, A., and Gwynne, S. (2016). "The collection and compilation of school evacuation data for model use." *Safety science*, 84, 24-36.

D.M (2015). "Approvazione di norme tecniche di prevenzione incendi, ai sensi dell'articolo 15 del decreto legislativo 8 marzo 2006, n. 139." Italy.

D.M (2017). "RTV Scuole" del Codice P.I. - att. n. 67 del DPR n. 151/2011 esclusi "asili nido"."

De Gloria, A., Bellotti, F., and Berta, R. (2014). "Serious Games for education and training." *International Journal of Serious Games,* 1(1).

Dimyadi, J. A., Spearpoint, M., and Amor, R. (2007). "Generating fire dynamics simulator geometrical input using an IFC-based building information model."

Feng, L. N., and Xiao, Z. (2018). "A fire drill training system based on vr and kinect somatosensory technologies." I*nternational Journal of Online and Biomedical Engineering (iJOE)*, 14(04), 163-176.

Feng, X., Cui, R., and Zhao, J. "The Effectiveness of Virtual Reality for Studying Human Behavior in Fire." *Proc., International Conference on Virtual, Augmented and Mixed Reality,* Springer, 13-21.

Finney, M. A. (1998). *FARSITE, Fire Area Simulator--model development and evaluation,* US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Gai, G., Cartapati, E., Mazzaro, M., De Bartolomeo, D., Cancelliere, P., and Ponziani, F. (2016)."UTILIZZO DEI METODI AVANZATI DELLA FIRE SAFETY ENGINEERING PER LA PROGETTAZIONE DELLA SICUREZZA ANTINCENDIO."

Glasa, J., and Steckova, V. "Computer simulation of fire dynamics in industrial hall." *Proc., Journal of Physics: Conference Series,* 012136.

Guo, H., Li, H., Chan, G., and Skitmore, M. (2012). "Using game technologies to improve the safety of construction plant operations." *Accident Analysis & Prevention,* 48, 204-213.

Kinateder, M., Ronchi, E., Nilsson, D., Kobes, M., Müller, M., Pauli, P., and Mühlberger, A. "Virtual reality for fire evacuation research." P*roc., 2014 Federated Conference on Computer Science and Information Systems*, IEEE, 313-321.

Kobes, M., Helsloot, I., De Vries, B., Post, J. G., Oberijé, N., and Groenewegen, K. (2010). "Way finding during fire evacuation; an analysis of unannounced fire drills in a hotel at night." *Building and Environment,* 45(3), 537-548.

Korhonen, T., and Hostikka, S. (2009). "Fire dynamics simulator with evacuation: Fds+ Evac: Technical reference and user's guide."

Langston, P. A., Masling, R., and Asmar, B. N. (2006). "Crowd dynamics discrete element multi-circle model." *Safety Science,* 44(5), 395-417.

Lee, E. A.-L., and Wong, K. W. (2014). "Learning with desktop virtual reality: Low spatial ability learners are more positively affected." *Computers & Education,* 70 9, 49-58.

Lovreglio, R., Duan, X., Rahouti, A., Phipps, R., and Nilsson, D. (2020). "Comparing the effectiveness of fire extinguisher virtual reality and video training." *VIRTUAL REALITY.*

Lu, X., Yang, Z., Xu, Z., and Xiong, C. (2020). "Scenario simulation of indoor post-earthquake fire rescue based on building information model and virtual reality." *Advances in Engineering Software,* 143, 102792.

McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., and Overholt, K. (2013). "Fire dynamics simulator user's guide." *NIST special publication,* 1019(6).

Mell, W., McNamara, D., Maranghides, A., McDermott, R., Forney, G., Hoffman, C., and Ginder, M. (2011). "Computer modelling of wildland-urban interface fires." *Fire & Materials.* San Francisco.

Milgram, P., and Kishino, F. (1994). "A taxonomy of mixed reality visual displays." *IEICE TRANSACTIONS on Information and Systems*, 77(12), 1321-1329.

Oliva, D., Somerkoski, B., Tarkkanen, K., Lehto, A., and Luimula, M. "Virtual reality as a communication tool for fire safety-Experiences from the VirPa project." *Proc., GamiFIN,* 241-252.

Poole, B. R. (2012). "Ordinary people and effective operation of fire extinguishers."

Ren, A., Chen, C., Shi, J., and Zou, L. "Application Of Virtual Reality Technology To Evacuation Simulation In Fire Disaster." *Proc., CGVR,* Citeseer, 15-21.

Rüppel, U., and Schatz, K. (2011). "Designing a BIM-based serious game for fire safety evacuation simulations." *Advanced engineering informatics,* 25(4), 600-611.

Scott, J. H. (2005). *Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model,* US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Shen, T.-S., Huang, Y.-H., and Chien, S.-W. (2008). "Using fire dynamic simulation (FDS) to reconstruct an arson fire scene." *Building and environment,* 43(6), 1036-1045.

Smith, S. P., and Trenholme, D. (2009). "Rapid prototyping a virtual fire drill environment using computer game technology." *Fire safety journal,* 44(4), 559-569.

St. Julien, T. U., and Shaw, C. D. "Firefighter command training virtual environment." Proc., *Proceedings of the 2003 conference on Diversity in computing,* 30-33.

Stroup, D., and Madrzykowski, D. (2003). "Heat Release Rate Tests of Plastic Trash Containers." *Report of test FR4018, National Institute of Standards and Technology, Gaithersburg, MD.*

Thompson, P. A., and Marchant, E. W. (1995). "A computer model for the evacuation of large building populations." *Fire safety journal,* 24(2), 131-148.

Wang, B., Li, H., Rezgui, Y., Bradley, A., and Ong, H. N. (2014). "BIM based virtual environment for fire emergency evacuation." *The Scientific World Journal,* 2014.

Williams-Bell, F. M., Kapralos, B., Hogue, A., Murphy, B., and Weckman, E. (2015) "Using serious games and virtual simulation for training in the fire service: a review." *Fire Technology,* 51(3), 553-584.

Xu, Z., Lu, X., Guan, H., Chen, C., and Ren, A. (2014). "A virtual reality based fire training simulator with smoke hazard assessment capacity." *Advances in engineering software,* 68, 1-8.

Zanut, S., Ronchi, E., and Cosi, F. (2017). "Fuori tutti, c'è un incendio a scuoa…ma è solo una simulazione ".