COMPDYN 2019
7th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Crete, Greece, 24–26 June 2019

FIRE EMERGENCY EVACUATION IN A SCHOOL BUILDING THROUGH VR

G.P. Cimellaro[1], M. Domaneschi[1], M. De Iuliis[1], V. Villa[1], C. Caldera[1], A. Cardoni[1]

[1] Politecnico di Torino
Corso Duca degli Abruzzi, 24 - Torino
e-mail: giampaolo.cimellaro@polito.it; marco.domaneschi@polito.it; melissa.deiuliis@polito.it; valentina.villa@polito.it; carlo.caldera@polito.it; alessandro.cardoni@polito.it

Abstract

The problem of emergency evacuation of public buildings intended to accommodate large numbers of people is critical. Modern technologies such as the use of numerical simulations, virtual and augmented reality, and Agent Based models represent an opportunity to study behaviors that are difficult to reproduce in real life (e.g. explosions and fires emergencies). This may allow to improve new and existing structures with respect to such risks and therefore to improve the resilience of modern communities.
In this paper, the problem of emergency fire evacuation for an existing school in the hinterland of Milan is studied. A virtual reality-based system for the simulation of fire emergency response will be developed starting from the BIM model and then moving on to a platform that ensures the interaction between human and the virtual simulation environment. The spreading of the flames and smoke is based on fire numerical simulation using computation fluid dynamic (CDF) software. Such simulation method may reproduce realistic fire processes and illustrate smoke movement by describing the configuration of fuel, ventilation, and fire source. The verification of the infrastructure response and the subsequent modification for a better emergency response represent the expected results of the research.

Keywords: Evacuation, Schools, Virtual Reality, Fire simulation

1 INTRODUCTION

Building emergency management can be generally defined as an integrated scientific methodology that concerns several aspects, such as emergency preplanning and psychological human behavior [1, 2]. It provides proper solutions for human safety in facing hazard events, such as earthquakes, floods, fire, etc. Among all, fire is one of the major disasters that occur in urban area and cause economic losses and human death [3]. Recent relevant studies have demonstrated that the high number of emergency casualties and injuries, especially in high-rising buildings, depends on the failure of timely evacuation of the occupants from the burning building [4, 5]. That is, the improper layout of the building structure and the psychological and physical responses of human beings may make the evacuation delayed. Indeed, human beings' behaviors are usually quite complicated to be predicted by mathematical models in emergency conditions. For instance, a panic mental state or abnormal behaviors induced by the spreading of flames and smoke or by the unfamiliarity with the building, may lead people choosing the wrong evacuation route.

Traditionally, fire emergency management deals with processes of preplanning evacuation (fire drill) or training in order to expose people, in particular firefighters, to real fire scenarios. Emergency evacuation training and drilling aim to improve humans' abilities in emergency conditions for evacuation and rescue, and to enhance fire emergency planning [6]. Hence, fire simulation becomes an important tool in fire investigation [7]. Nevertheless, actual fire training leads both social and economic disadvantages in finding resources, as well as safety risks in inhaling toxic gas for instance. That influences the validity and replicability of the results [8]. Problems with potentially dangerous training are identified to be remedied. Accordingly, VR training systems have been investigated by a number of researches as they seem to be a proper alternative to actual fire drill. That is, they allow a safe, low-cost and repetitive training environment for emergency evacuation [9-14]. The available VR technologies bear (i) to create an accurate and realistic fire environment where users can immerse and (ii) to identify the safest path in the course of training. Thus, an accurate and rational visualization of fire and smoke is significant for effective rescue in virtual training, as actual fire is a continual dynamic process and smoke parameters change along with time. A large number of computational fluid dynamics (CDF) computer software, such as the Fire Dynamics Simulator (FDS) developed by the National Institute of Standards and Technology (NIST) of United States, are widely applied in various fire investigations [15, 16], as they study accurately the dynamic propagation of fire and smoke. For instance, Cha et al. [17] integrated a VR fire-training simulator with fire dynamics data in order to develop a real training procedure for general public or inexperienced firefighters. Ren et al. [18] also integrated fire numerical simulation with VR environment for fire evacuation simulation. Similarly, Yi et al. [19] proposed a calculation method for the simulation of chemical disaster emergency drills by using the virtual simulation control. However, the study was considered complicated since it required a fuzzy integrated model. An arson fire scene was reconstructed using fire dynamic simulation (FDS) by [20]. In their work the fire scene is reproduced by demonstrating the fire development and the smoke movement through the configuration of fuel, ventilation, and fire source. Virtual simulation technology has been also developed using the 3D visualization for the earthquake rescue drill real seismic simulation in order to analyze difficulty, cost, and effect [21].

Although the rapid development of Virtual Reality (VR) technology have made it possible to overcome the limitations described above, the representation of a real human behavior in emergent situation [18], and the assessment of information interaction between the building and the building user [14] are still challenging.

This paper introduces a framework that combines BIM as a building information provider and computational fluid dynamic computer software as spreading of flame and smoke simulator in order to build an adaptable virtual reality environment with the scope of enhancing fire evacuation plans. The realistic reconstruction of the fire scene is possible by a joint application of VR and KAT VR platform in order to recognize the human actions through the KAT VR equipment and software. A secondary school scenario placed in the hinterland of Milan is investigated for validating the proposed simulator. Results show that the work is suitable and is of benefit for people trapped in burning buildings in identifying the safest path for evacuation or rescue, as well as for a consequent modification of the building layout in order to perform a better emergency evacuation. The system can be used to train people to evacuate under emergency situations or firefighters to perform a rescue during a fire event. Furthermore, it could be used to evaluate existing infrastructures, often designed with outdated standards, against multiple risks, such as fire and earthquake, and the study of emergency evacuation.

Technical details are introduced in the following sections. The paper is organized as follows: Section 2 explains the architecture of the system and the methodology; Section 3 describes the numerical simulation of the fire and smoke spreading; Section 4 shows the case application for fire evacuation. Finally, the conclusions are drawn in Section 5 together with the recommendations for future work.

2 SYSTEM ARCHITECTURE

The architecture of the system consists of four major modules, as illustrated in Figure 1:

1- Modelling: the Unity3D model and the FDS model are both created according to the building information (BIM);
2- Fire Dynamics Simulation: the fire dynamics simulation is performed by FDS software and results are then integrated with the VR model;
3- Virtual Environment: the VR model is built, and it becomes interactive by using C++ plug-ins;
4- Emergency Evacuation Simulation: the fire training in a realistic hazardous scenario is carried out through the KAT VR platform for evacuation and rescue.

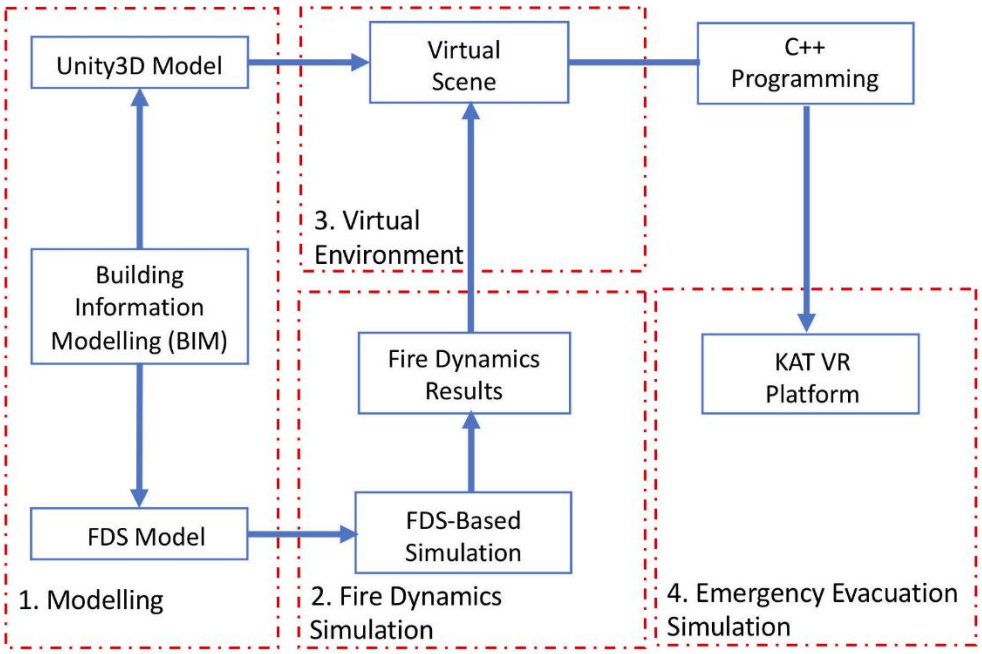

Figure 1: Flowchart of the proposed fire simulator.

The proposed framework uses a BIM authoring tool (Autodesk Revit) as a building information provider. BIM can play a significant role in making available building information under an emergency scenario, as it is able to provide comprehensive data format and integrated process [22]. Building information is then transferred both to a game engine software (Unity3D) in order to create a high-quality virtual environment and to a computational fire dynamics software for accurately predicting the evolution of fire in the virtual environment. Unity3D is one of the most important game engine software and it can be integrated with virtual reality equipment to satisfactorily reproduce the virtual environment.

Simulation of fire scene is the basis of the proposed system. In the creation of a virtual building environment in fire condition the main challenge to be cleared up regards the visualization of flames and smoke spreading. Generally, the spreading process is hard to predict, and therefore, it is simplified in many studies [23]. Moreover, a simple sketch to simulate flames and smoke is not sufficient to study a real fire on emergent evacuation process [24].

In this work, a fire numerical simulation software to calculate and predict the fire propagation is implemented. The integration of fire numerical simulation and virtual reality allows the user to be immersed in a computer-generated fire scenario, which is dangerous and expensive to perform in real life [25]. Data on fire evolution in the virtual scenario, such as burning time, temperature, height of flame and smoke layer and spreading, etc. are obtained using the Fire Dynamics Simulation (FDS), a computational fluid dynamics (CDF) simulation of fire-driven fluid flow developed by the National Institute of Standards and Technology (NIST). Based on the CDF data of FDS, an accurate virtual smoke and flames visualization is created. That is, results from the numerical simulation are integrated with the Unity3D model that has been previously developed. In order to allow the user to interact and navigate within the virtual scenario different plug-ins, which are libraries of native code written in C++ programming language have been integrated. Plug-ins incorporated into the Unity3D server allow the virtual environment to call functions from these libraries, such as walking, grabbing objects, etc. with the objective of increasing realism of the virtual fire disaster.

Finally, once the virtual environment has been designed and developed through opportune scripts, the Emergency Evacuation Simulation can start. In the last step of our simulator, a VR platform and body sensors are applied. In such way, the user becomes the first-player of the virtual scene controlling his/her own movements through VR sensors in order to improve the perception of the fire evacuation experience.

Fire numerical simulation and flames and smoke visualization are described in the following section.

3 SIMULATION OF FIRE SCENARIO

3.1 Simulation of the flames and smoke spreading using FDS

Fire Dynamics Simulator (FDS) is a calculation model, which predicts smoke caused by fire, wind, and ventilation system through the fundamental equations of fluid flow, known as the Navier-Stokes equations. It has been developed by the National Institute of Standards and Technology (NIST) specifically for the analysis of fire scenario. FDS model forecasts flow velocities and temperatures by dividing the space into discrete volutes with specified thermo physical properties with a margin of error of 5-20% [26].

In order to accurately predict the dynamic evolution of fire in virtual environment, the input data must be defined. Input parameters can be classified as:

- Mesh: creating a space that contains all the geometry of the system divided by cubic-shaped elements of a given size that will condition the accuracy of the test;
- System Geometry: drawing the geometry from scratch of import it from another software (e.g. AutoCAD);
- Material of elements: defining the type of material of the element, and therefore its thermal conductivity;
- Boundary conditions: defining the characteristics at the borders of the mesh, for instance if the passage of smoke is allowed or not;
- Point of ignition of the flame: determining both the physical place where the flame is born and from which it propagates and the energy of the flame;
- Time duration of the test in seconds;
- Wind direction and intensity

After the fire simulation has been finished, data obtained in output are:

- Flame and smoke propagation as function of time;
- Temperature of the simulation;
- Percentage of various chemical components that make up the air.

The simulation results are displayed by using the Smokeview program, which is the post-processor of FDS. That is, it is a scientific software designed for the visualization of the fire model calculated by FDS. Finally, such output data are integrated with the virtual model in order to reproduce a realistic fire scenario.

3.2 VR Fire simulation

A VR fire training simulator is developed according to the FDS data through a graphics game engine Unity3D and a VR platform. After the fluid dynamics simulation of smoke and flames propagation by the CDF software, results are imported into the Unity3D model to be

integrated into the virtual reality simulation. Among the output data provided by the FDS calculation there are no files compatible for this purpose; thus, some steps of data processing are required. The first step is made through the open source three-dimensional modeling software Blender, which allows to directly import FDS files providing a user interface to modify them. On Blender, smoke and flames display is processed, meshed and exported in an output file compatible with the software ParaView. ParaView is an open source multi-platform software for scientific data analysis and visualization. It deals with the process and execution of data in 3D model. That is, data are post-processed and converted into a vector data format. The last step of the fire visualization within the virtual model is to import the processed file in Unity3D in order to set the virtual fire scene.

Once the fire visualization has been reproduced, the connection among KAT VR platform and C++ programming scripts is employed since the user can interact with the virtual environment and move in any direction observing the fire spreading within the virtual scenario like a first-person video game. That's is possible by using a headset sensor that allows the user to be immersed inside the virtual scenario, while the navigation is controlled by shoe cover sensors. KAT VR sensors are connected to the Unity3D model through opportune plug-ins that consent the virtual model to receive the user's operations in real time. Moreover, the interaction between the user and the environment is also possible in our system by implementing the functionality of grabbing objects with the use of handset sensors. Thus, with this functionality, for instance, the user can pick up firefighting equipment to extinguish the fire and perform the fire training within the virtual environment.

4 APPLICATION OF THE SYSTEM: FIRE RESCUE IN A SECONDARY SCHOOL

To test the practicality of the system, a fire scenario in a 2-floor secondary school in which the gym is on fire, is investigated. First, Unity3D is employed to create the realistic 3D model of the school using information from the BIM model; FDS is used to numerically simulate the fire scenario and then the simulation results are implemented in the Unity3D model according to the method described above, in order to create a realistic fire emergency condition, and consequently to perform emergency evacuation through the VR platform. In FDS simulation the fire source is designed as a box on the platform of the gym and it is assumed to be caused by a short circuit that has damaged the electrical system of the structure. The fire evolution is simulated with the combustion reaction of wood and plastic. In addition, a temperature of the internal air of the gym is fixed at 20°C. The time of the simulation is 300 seconds.

FDS output results from SmokeView at different time of the simulation are illustrated in Figure 2.

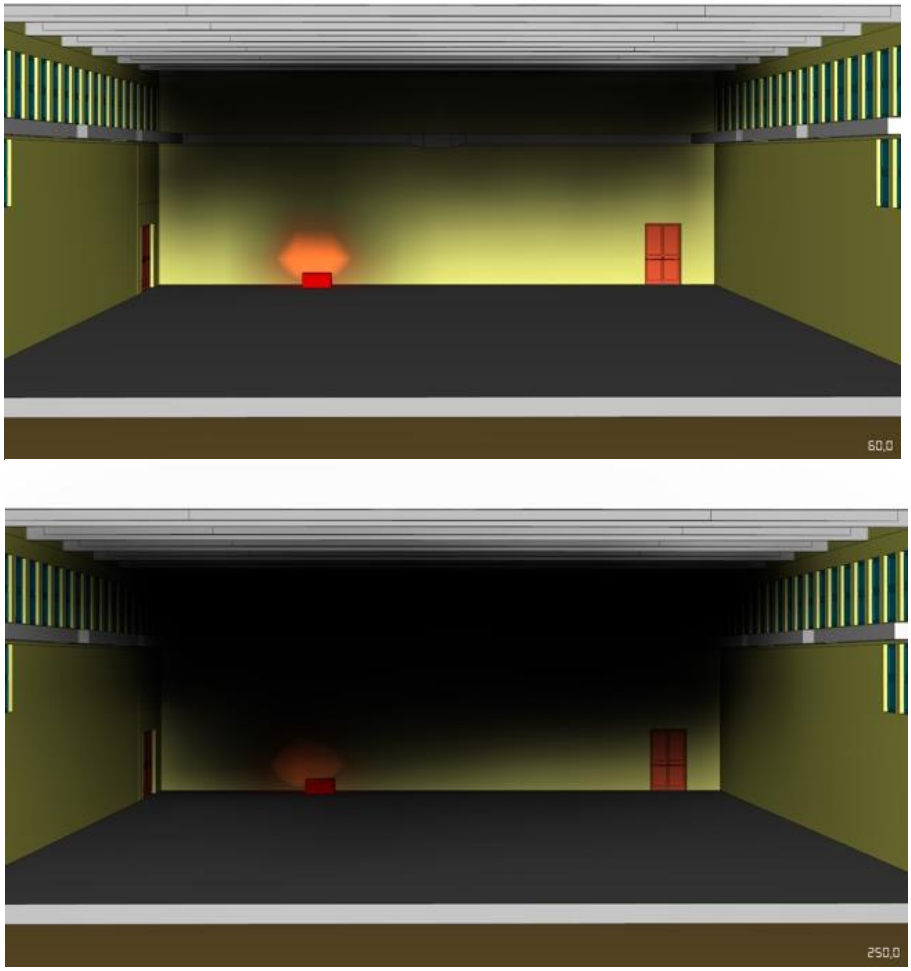

Figure 2: FDS fire simulation at 60nd and 250nd seconds

The figure shows the course of flames and smoke during the simulation at 60nd and 250nd seconds. As it is shown, at first smoke propagates upwards then stratifies under the ceiling. Once vertical barriers (i.e. walls) have been reached, clouds of smoke start spreading along the barriers downwards. The same scenario is reproduced in the virtual gym model (Figure 3) through Unity3D.

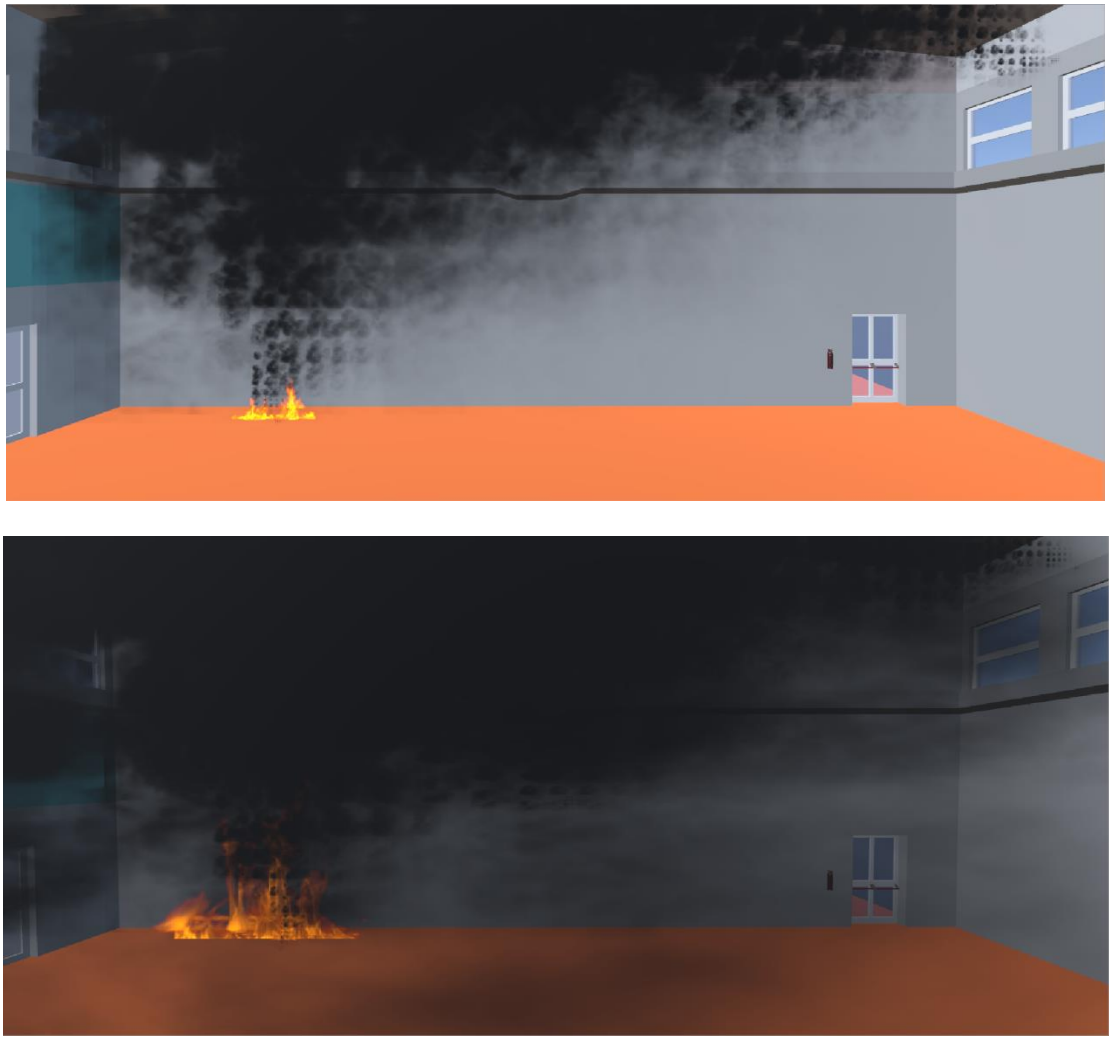

Figure 3: Fire scenario in Unity3D at 60nd and 250nd seconds

In Unity3D model, fire and smoke are finished with the particle system, which typically includes a particle emitter, a particle animator player, and a particle renderer. To simulate the real fire effect, particle collider should be added to objects. Accordingly, all walls have particle colliders so that when flames and smoke collide with them, barrier and reflection occur. The distribution of smoke in Figure 3 is consistent with the FDS results, and the fire scenario provides an effective interactive environment for performing firefighting training.

5 CONCLUSION

A VR simulator for evaluation of emergency evacuation performance is developed in the paper. Based on the BIM model, FDS fire dynamics data are designed in order to provide a realistic fire environment and to create an interactive performance in the practice of virtual evacuation. Integrating FDS output data into the virtual Unity3D model a VR fire training simulator through the use of a VR platform is proposed. In this way the user can perform emergency evacuation drilling in the virtual environment at first-hand by using VR sensors and C++ plug-ins. The application of the system to a secondary school placed in the hinterland of Milan demonstrates that the presented simulator may allow trainees, such as firefighters, school em-

ployers, and students to experience realistic fire scenario for identifying the safest path for evacuation or rescue. Thus, results from the virtual simulation may help architects and engineers to improve regulations of Italian school buildings as the majority of existing schools were built in the 70s and can therefore be considered outdated. Moreover, the fire scenario reconstruction supported by platform and computer simulation can also offer important information on the human behaviors under emergent conditions. Further research will be carried out by applying the simulator to compare different evacuation paths integrating the smoke hazard assessment.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Research Council under the Grant Agreement n°ERC_IDEalreSCUE_637842 of the project IDEAL RESCUE - Integrated DEsign and control of Sustainable CommUnities during Emergencies.

REFERENCES

[1] Gao, Y., C. Li, and Y. Zhao. *The review of emergency management research*. in *2011 2nd IEEE International Conference on Emergency Management and Management Sciences*. 2011.

[2] Yan, G.J.P.E., *Research and design on integrated management system of digitalized emergency preplan.* 2011. **24**: p. 713-720.

[3] Flynn, J.D.J.Q., MA: National Fire Protection Association, *Characteristics of home fire victims.* 2010.

[4] Fahy, R.F. and G. Proulx. *Toward creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling*. in *2nd international symposium on human behaviour in fire*. 2001. Boston, MA, USA.

[5] Gershon, R.R., et al., *The World Trade Center evacuation study: Factors associated with initiation and length of time for evacuation.* 2012. **36**(5-6): p. 481-500.

[6] Peacock, R.D., B.L. Hoskins, and E.D.J.S.S. Kuligowski, *Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories.* 2012. **50**(8): p. 1655-1664.

[7] McGrattan, K.B., et al., *Fire Dynamics Simulator--Technical Reference Guide*. 2000: National Institute of Standards and Technology, Building and Fire Research ….

[8] Lawson, G., *Predicting human behaviour in emergencies*. 2011, University of Nottingham.

[9] Chittaro, L. and R. Ranon. *Serious games for training occupants of a building in personal fire safety skills*. in *2009 Conference in Games and Virtual Worlds for Serious Applications*. 2009. IEEE.

[10] Smith, S. and E.J.V.r. Ericson, *Using immersive game-based virtual reality to teach fire-safety skills to children.* 2009. **13**(2): p. 87-99.

[11] Wasfy, T.M. and A.K.J.A.i.E.S. Noor, *Visualization of CFD results in immersive virtual environments.* 2001. **32**(9): p. 717-730.

[12] Smith, S.P. and D.J.F.s.j. Trenholme, *Rapid prototyping a virtual fire drill environment using computer game technology.* 2009. **44**(4): p. 559-569.

[13] Manca, D., S. Brambilla, and S.J.A.i.E.S. Colombo, *Bridging between virtual reality and accident simulation for training of process-industry operators.* 2013. **55**: p. 1-9.

[14] Rüppel, U. and K.J.A.E.I. Schatz, *Designing a BIM-based serious game for fire safety evacuation simulations.* 2011. **25**(4): p. 600-611.
[15] Olenick, S.M. and D.J.J.J.o.f.p.e. Carpenter, *An updated international survey of computer models for fire and smoke.* 2003. **13**(2): p. 87-110.
[16] McGrattan, K., et al., *Fire dynamics simulator (version 5) technical reference guide.* 2007. **1018**(5).
[17] Cha, M., et al., *A virtual reality based fire training simulator integrated with fire dynamics data.* 2012. **50**: p. 12-24.
[18] Ren, A., et al., *Simulation of emergency evacuation in virtual reality.* 2008. **13**(5): p. 674-680.
[19] YI, T., Q. ZHU, and P.J.C.J. LIU, *An emergency drilling-based fuzzy expert system for chemical safety [J]*. 2011. **10**.
[20] Shen, T.-S., et al., *Using fire dynamic simulation (FDS) to reconstruct an arson fire scene.* 2008. **43**(6): p. 1036-1045.
[21] WANG, Y. and Z.-h.J.C.S. FAN, *Research on Earthquake Rescue Drilling Simulation System [J]*. 2013. **1**.
[22] Wang, B., et al., *Intelligent building emergency management using building information modelling and game engine.* 2013. **7**(3 (B)): p. 1017-1023.
[23] Freund, E., J. Rossmann, and A. Bucken. *Fire training in a virtual-reality environment*. in *Stereoscopic Displays and Virtual Reality Systems XII*. 2005. International Society for Optics and Photonics.
[24] Ren, A., et al. *A virtual reality-based system for the fire fighting and emergency response*. in *Proceedings-Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Canada*. 2006.
[25] Bukowski, R. and C. Sequin. *Interactive simulation of fire in virtual building environments*. in *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*. 1997. ACM Press/Addison-Wesley Publishing Co.
[26] Forney, G.P., et al., *Understanding fire and smoke flow through modeling and visualization.* 2003. **23**(4): p. 6-13.