Design and Development of a Dynamic Fire Signage System for Building Evacuation: A VR Simulation Study

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Abstract. The paper presents a dynamic fire signage system for simulating emergency evacuation in the case of fire through dynamic pathfinding towards the nearest and safest exit in a virtual environment. Conventional fire signs and fire escape plans are becoming outdated and less effective due to their static nature and inability to adapt to different emergency scenarios. Experimental studies have shown that dynamic signs can be effective in guiding users of any age and can highly influence their direction choices during evacuation. A VR tool for simulating emergency evacuation through dynamic pathfinding towards the safest and nearest exit was designed using a BIM model as a basis to create a virtual environment for the simulation. Newly created fire signals, referred to as Fire Signal Cubes (FSCs) were used. They were specifically developed and implemented for this project as input for the node database and pathfinding algorithm to define navigable spaces. The FSCs have from one to four active sides, depending on their position in the floor plan and their relation to pathways and exit doors. Each side of the FSC that faces a path, or an exit door is active, and the FSC can show the correct signal according to the input of the pathfinding algorithm that instantly calculates the safest escape path. The paper provides a detailed description of the methodology and presents the results of implementing the dynamic pathfinder using a BIM model of an office environment.

Keywords: Virtual reality · dynamic fire signal · emergency evacuation · BIM · Unity

1 Introduction

Fire evacuation is a critical aspect of building safety that has been a subject of interest in the Architecture, Engineering, Construction, and Operations (AECO) industry for decades. Traditional methods of fire evacuation involve the use of fire alarms and signage to guide occupants towards the nearest exit. However, these methods are becoming

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L. T. De Paolis et al. (Eds.): XR Salento 2023, LNCS 14218, pp. 157–171, 2023.
https://doi.org/10.1007/978-3-031-43401-3_10

outdated and do not take advantage of the new and advanced technologies emerging in the AECO industry. The use of Building Information Modelling (BIM) and Virtual Reality (VR) environments have shown great potential in creating strategies that enhance safety and reduce time in emergency situations [1, 2].

The current literature regarding the application of VR for fire safety has demonstrated potential in improving fire evacuation planning and training. Some studies have explored the use of VR environments to enhance emergency response times [3] and to create more efficient evacuation paths based on specific conditions [4]. However, most studies have primarily focused on using VR for training [5], BIM for building risk management [6] and evacuation plan efficiency [7].

Although the results of these studies are encouraging, there is still a gap in the investigation of the interoperability between BIM and VR for fire safety, as well as the implementation of innovative techniques for signaling fire escape routes. Traditional fire signage is becoming outdated with the new and advanced technologies emerging in the AECO industry. Thus, there is a need for a dynamic system that can adapt to different fire scenarios and provide real-time information about the best escape path, reducing the time it takes to leave the building and preventing people from being blocked between emergency doors and fire or smoke.

The purpose of this study is to develop a dynamic fire signal that offers real-time information on the safest escape route during a fire emergency based on the location of the fire or smoke source. The tool was developed using a pathfinder algorithm that utilizes BIM data to provide real-time updates. The study also aimed to assess the effectiveness of VR in fire evacuation simulations, explore the interoperability between BIM and VR, and evaluate the use of dynamic fire signals in identifying the correct fire escape routes. Using VR for this purpose has been shown to be a safer and more efficient use of resources and time.

The primary goal of our study is to enhance building safety and safeguard users by introducing a new method of guiding individuals during emergencies. Our system aligns with existing building management and operation technologies, leveraging data extracted from digital simulations. By utilizing a VR environment, we highlight the potential benefits of incorporating advanced technologies across all areas of the AECO industry. The expected outcomes include a reduced evacuation time and improved safety measures for building occupants. Additionally, our research will contribute to the growing body of literature on VR and BIM interoperability for fire evacuation simulations, thereby adding to the current knowledge on building safety.

As a result, we developed a three-dimensional cube that serves as an interactive tool for signaling fire escape routes. To determine the optimal evacuation path for building occupants during a fire emergency, we employed a pathfinder algorithm that considers the location of emergency exits and the source of the fire. This information is transmitted to the cube, which then provides guidance to users towards the safest path. To assess the effectiveness of the application, a virtual environment was created using Unity and tested by human users.

The paper has five sections. Section 2 presents the state of the art on the topics of fire safety, VR and BIM. Section 3 details the methodology used to create the smart system and the workflow between the integration of BIM and VR tools. Section 4 discusses the results and implementation of the system in a virtual environment. Finally, Sect. 5 presents a discussion on the paper and prospects for future research.

2 State of the Art

Fire safety is one of the primary concerns for Architecture, Engineering, Construction, and Operations (AECO) professionals as it ensures the safety of building users. Fire Safety Engineering (FSE) is a process that uses engineering principles to create or assess designs in the built environment to protect occupants [8]. Its main objective is to prevent fire emergencies and secure occupants, buildings, and other facilities. In general, the design of safe spaces considers possible fire hazards, such as materials and configurations that could lead to a fire outbreak. Additionally, FSE strategies are employed to mitigate the impact of fire and ensure occupant safety in the event of an emergency. Many building regulations incorporate these strategies to ensure the safety of building occupants. Although different countries have various regulations, similarities exist in terms of core aspects of fire safety [9, 10], highlighting the challenges involved in providing a safe environment for users.

The main objective during a fire emergency is the safe evacuation of building occupants. The escape routes are crucial as they represent the path that leads the building occupant to a safe space. Building regulations typically specify a maximum distance to safe exits [11], which can be increased when the escape route has aids such as sprinklers, light and sound alarms, and so on. The success of the route also depends heavily on how familiar the building users are with it [12, 13].

However, some building types, such as airports, shopping malls, and performance halls, have mostly transient occupants. In such cases, the guidance of occupants depends solely on the use of signs for directing safe exits, which are widely used in building designs to compensate for a lack of user awareness or possible behavior changes during a fire. Studies underscore the importance of designing effective signage for emergency exits to ensure that people can safely and quickly evacuate a building during an emergency [14, 15].

Regarding the building type, escape routes should always be flagged with clear signs to guide users when navigating the path. The goal is to lead the occupants in a quick evacuation of the building during an emergency, reducing the number of casualties. Training and drills are regular practices used in fire protection methodologies. Training helps occupants acquire knowledge of the spaces and escape routes, while drills simulate an emergency without putting the users at risk. These practices are essential in making occupants aware of their environment and training them for potential casualties [15].

Virtual Environments (VE) are used in different sectors for training purposes when there is a risk of harming the users in real-case situations. For example, VE simulations are used in flight training for pilots. One of the VE applications, the Virtual Reality (VR) provides users with a detailed, controlled, and safe experience that is not achievable in other scenarios. Therefore, the use of VR for safety purposes in the construction sector is highly promising. VR has been employed in workspace planning testing for a construction project in Italy, where the simulation helped identify potential safety hazards and improve the workspace configuration [16]. Additionally, VR has been used to study fire behavior and how to prevent and protect people and facilities [17, 18]. Numerous studies have focused on this subject, analyzing human responses to fire escapes using VR tools for testing and studying the potential applications of virtual reality environments to train construction workers regarding safety concerns [19]. Other studies create mathematical simulations for improving escape paths and use VR to test the final results [20].

The main advantage of using VR for safety training is the ability to simulate a real-case scenario without the risk of physical harm. However, a big disadvantage is that human behavior changes when the person knows there is no real threat in the simulation environment [1].

BIM (Building Information Models) is widely used in the AECO (Architecture, Engineering, Construction, and Operations) industry. BIM creates digital environments to simulate real-world scenarios [21], providing benefits to the industry, including the ability to study the behavior of fire and smoke. BIM data can be used across platforms to simulate scenarios according to the necessity of each study.

Several studies show that the use of BIM models can improve fire safety in built assets [2]. Integrating BIM models with algorithms and applications can create escape paths based on data gathered from the environment [3]. For instance, a study uses a pathfinding algorithm and BIM model to create paths for workers on a construction site to ensure their safety [4]. Another study presents a dynamic escape plan for buildings using fire simulation to create safe escape routes during a fire event [22]. Additionally, a BIM 3D visual model with a mobile guiding system assists firefighters in locating risk areas and planning optimal rescue routes [23].

However, studies linking BIM, VR, and fire safety mostly relate to building inspections or professional training [3, 24, 25]. While many studies focus on the automatic updating and increasing efficiency of escape routes [4, 23], no studies combine the automatic creation of those paths with VR drills. Moreover, a study by [3] found that guidance during escape in an emergency is crucial. The difference in moving routes for the two trial groups when escaping a facility was heavily supported by personal experience. For those without previous knowledge of the building, the moving route was timelier and more complicated. Thus, the necessity of good signage emerges to protect real users during emergencies.

Furthermore, past research correlating VR and means of escape mostly concentrates in China [3, 4, 17, 22, 24, 26], with limited studies conducted in Europe where building age and type may differ significantly. Although these studies showcase innovative technologies, they do not represent a significant technological advancement in advancing means of escape. The systems to manage data from a building in distress may have changed, but guidance for users inside buildings still relies on traditional analog formats. In a study by [27], they present the idea of dynamic signing for fire escape. However, there is still a gap in the literature on this topic, such as exploring the combination of a new type of signage that integrates live data and management, such as through BIM, or the use of virtual simulations such as VR.

In summary, BIM is a valuable technology for the AECO industry that can improve fire safety. Nevertheless, more adaptable systems are necessary for all building types. Moreover, while innovative technologies exist, further research is needed to advance means of escape and improve guidance for users inside buildings during emergencies.

3 Methodology

3.1 Conventional Fire Signage System and the Premise for a Dynamic System

Conventional fire signs and fire escape plans have been the primary means of providing information on evacuation routes and emergency procedures in buildings for many years. However, the conventional fire signage system is becoming outdated and less effective for several reasons.

Firstly, conventional fire signs provide static information that cannot adapt to different emergency scenarios. Many studies are showing that conventional signs may not be visible in certain areas of the building or may not be easily understandable by the occupants in moments of emergency. So, their effectiveness becomes questionable [27].

On the other hand, experimental studies have shown that dynamic signs can be effective in guiding users of any age and highly influencing their direction choices during evacuation. Networked digital escape routes could significantly improve the safety and efficiency of the process [18].

Secondly, a general and static fire escape plan may not provide clear and actionable instructions due to the complexity of the building and the lack of familiarity with it. This can lead to delays and confusion for the occupants and put their lives at risk [27].

The rapid developments of the AECO industry in the design and construction of the built environment demand the same regarding their safety. On these premises and with the technological means available, we built a dynamic fire signage system and simulated it in a VR environment. The concept of dynamic fire signs has been early introduced in various studies [27, 28], but its definition in the standards and regulations is still utterly inferior to the conventional one. In this study, the term dynamic fire sign refers to a fire sign that is able to change its display of indications in real time according to an instant input from a monitoring and signaling system, leading the occupants to the nearest safe exit. In this project the monitoring and signaling system is simulated in the VR environment, along with the fire scene.

3.2 Concept of the VR Tool

In this paper, we present the design and development of a VR tool for simulating emergency evacuation in case of fire, using dynamic path finding to determine the safest and nearest exit. We used a BIM model as the foundation to create the virtual environment for the simulation. A fire signal is placed at every crossing of the pathways in the floor plan. In this paper, we will refer to it as Fire signal cube (FSC). Depending on the number of pathways, each side of the FSC is equipped with signs for every available direction (left, right, forward) and the Stop sign. The FSCs serve as an input to create the database of nodes and the relationships between them for the path finding algorithm. Finally, we created a VR environment to simulate a lifelike evacuation scenario and implement the dynamic pathfinder.

3.3 BIM Model and Creation of the FSC

For this project, a BIM model of the Fraunhofer Italia office environment was used and adapted to simulate the escape scenarios added. The model is an identical representation of our current environment, with a total area of 922 m^2. It is composed of one floor, eleven rooms, multiple corridors, open areas, two staircases, and two exit doors for evacuation. Autodesk Revit environment was used to build and modify the model during this study.

For the scope of this study, we have made additions to the model by incorporating newly created fire signals that were specifically developed and implemented for this project. They were created as BIM objects containing geometric and non-geometric attributes [29] that serve as input for the node database's pathfinding algorithm to define the navigable spaces. Sixteen FSCs are placed in the model to cover the fire escape evacuation for the whole area (see Fig. 1). Each one of them is placed where two or more paths intersect and where an emergency exit door is present. An ID letter is assigned to each of the FSCs, ranging from A to P. Being positioned in front of each path at every crossing, the fire sign will be highly visible to the occupants and will provide a clear and sole indication of the direction that they must follow. This would lower the level of confusion and stress among the occupants, as they have fewer chances to make independent decisions in a moment of emergency evacuation.

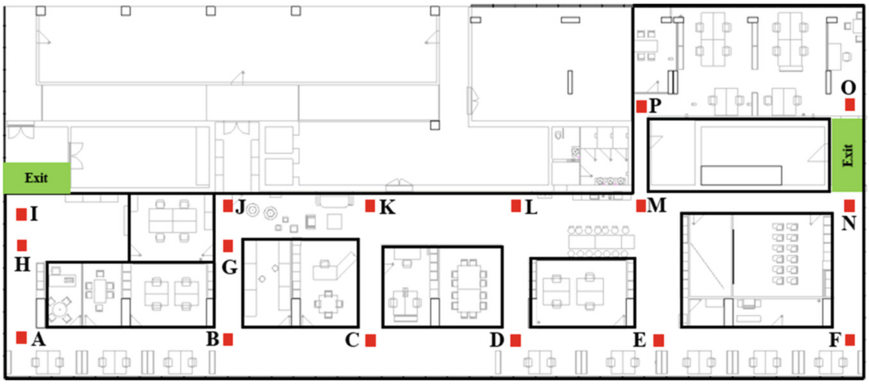

Fig. 1. Placement of the Fire signal cubes (FSC) in the floor plan of the office model.

The FSC has from 1 to 4 active sides, depending on its position in the floor plan, its relations to the pathways, and the exit doors. The sides that face a path or an exit door are active. The sides that face a dead end (ex. a wall) are inactive.

Every side of the cube has the possibility to display four fire signals (stop, forward, left, and right) (see Fig. 2) depending on the location where it is placed, and the emergency situation presented. The FSC is capable of displaying the correct signal according to the input of the path finding algorithm that instantly calculates the safest escape path.

The FSC is created as a BIM object using Autodesk Revit. Three identity parameters are added to it as Revit family parameters: the "ID" parameter, the "neighbor" parameter, and the "exit" parameter. Each of the FSCs has a unique ID, which is a letter from A to P that fills the ID parameter. The adjacent FSCs of each FSC are considered neighbors, and their IDs are inserted in the "neighbor" parameter of each of the FSCs. The "exit" parameter is active in the case that FSC leads directly to an emergency exit door and inactive in every other case. These three parameters are read by the pathfinding algorithm, and according to the correct path, each sign is analyzed and activated. After determining the shortest path, the FSCs activate the signs that direct towards the available neighboring FSC until the exit door is reached.

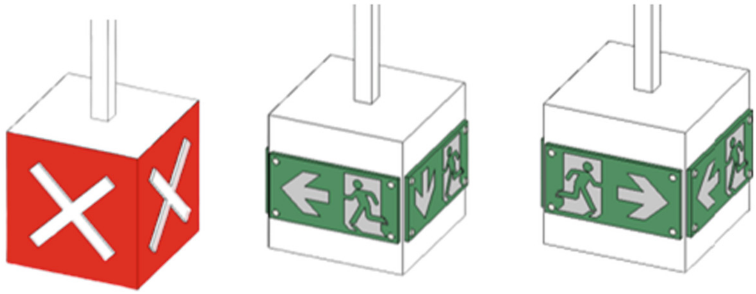

Fig. 2. Illustration of the Fire signal cube (FSC) displaying fire signals in three different evacuation scenarios.

3.4 Path Finding Algorithm

The basis for the dynamic adaptation of the fire signs that indicate the escape routes is the dynamic calculation of paths to the nearest exit. For a real case scenario, a path finder must provide results in real-time. For this reason, we discretized the problem and applied a rather simple search algorithm. The area of interest is discretized with nodes, where each FSC position represents one node. The relationships between the nodes — information about which nodes are neighbors and which nodes exist—is known from the digital building model and accessible to the path finder through a database. The database contains a list of nodes, in which each node has a unique identifier, a list of identifiers of the neighbors, a list of distances to the neighbors and a logical value indicating whether the node is an exit or not. Furthermore, that database is continuously updated in the sense that nodes that are within a certain distance of a fire event are excluded.

The implemented search algorithm takes a node database as input and returns the shortest path to an exit for each node in the form of a sequence of nodes that leads to the closest exit. A Breadth-First Search (BFS) approach [30] was conducted in this study. BFS discovers first all neighbor nodes before moving on to the next level (neighbors of the neighbor) until all nodes that are reachable from the root node are discovered. BFS has the advantage over other algorithms such as Depth-First Search (DFS), where first all nodes in one direction are discovered (all levels of the search tree), that it is guaranteed to find the optimal solution. Therefore, BFS generally takes longer to find a solution. For our specific case of the fire escape route, the implemented BFS algorithm returns all the possible paths to all the existing exits and then calculates the shortest path based on the total length of each path (see Fig. 3). It should be noted that we refer to the length as the physical distance measured in meters, whereas in typical search problems, the length is referred to as the number of steps from one node to another.

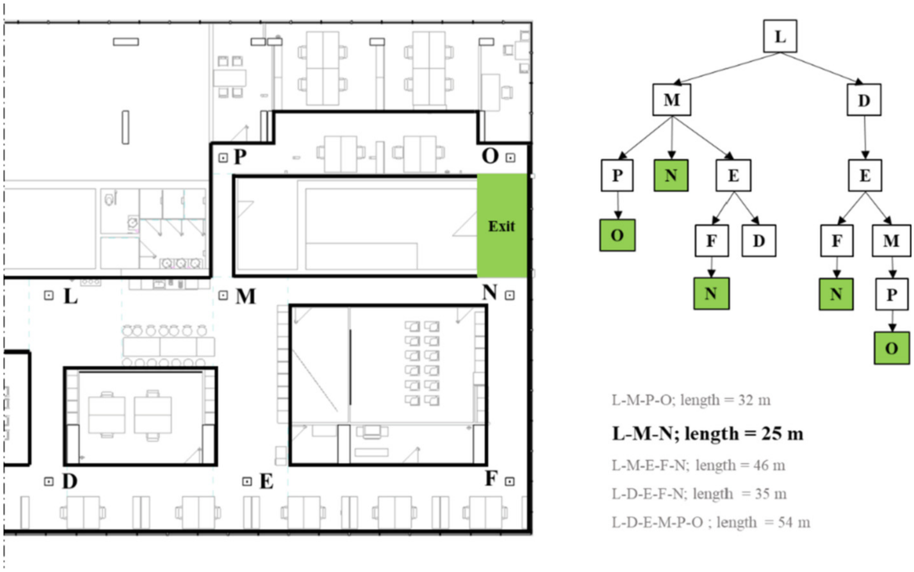

Fig. 3. Illustration of discretization of building floor plan (nodes denoted with capital letters) and example of exit path finding from node "L".

3.5 VR Escape Simulation

In order to create an immersive and lifelike emergency evacuation experience, a VR fire escape simulation has been defined. The VR experience should allow users to navigate through a virtual building and encounter realistic scenarios, such as burning objects, blocked exits, or smoke-filled hallways. To achieve this, the definition of the VR experience is based on a two-step approach, as shown in Fig. 4. Firstly, the realistic scenarios were created using Unity Reflect [31] and Unity (Unity Real-Time Development Platform) [32]. Unity Reflect can integrate seamlessly with multiple design tools, such as Autodesk Revit. This integration allows both the BIM model and associated data to be imported into Unity, which can then be used to create immersive VR simulations. Using this approach, the case-study's BIM model, including fire signage and related data, was imported into Unity. Afterwards, fire and smoke elements and path finding functionality were integrated into the model. The pathfinding algorithm was integrated by including C# scripts in the Unity project. During simulation the path finding algorithm is executed in every frame. This enables the identification of the safest evacuation paths based on the location of fire and smoke elements during run time. These elements were created using the *ParticleSystem* Unity component. It allows moving flames and smoke to be simulated, thus creating a lifelike fire scenario. In addition, the location of fire and smoke elements can be modified to simulate different fire scenarios.

Secondly the navigation system was defined using the Cyberith Virtualizer ELITE 2 [33] and the HP Reverb G2 VR-Glasses [34]. Cyberith Virtualizer ELITE 2 is a VR locomotion device that allows users to walk and run within a virtual environment. It has sensors that detect the user's movements and translate them into corresponding actions in the virtual environment, so that the user can react to a fire scenario in a more intuitive and realistic way. The locomotion device was integrated by including the *CVirtPlayerController Prefab* player object into the Unity project. The *CVirtPlayerController Prefab* consists of an abstract user representation and a set of functionalities for moving. Finally, the HP Reverb G2 VR-Glasses was set to work in conjunction with the locomotion device. This was done by integrating the *TrackedPoseDriver* component into the Unity project. In this way, users' movements, such as the position and orientation of the head, are tracked in real-time and translated into corresponding actions in the virtual environment. By immersing users in a realistic virtual environment, the VR-Glasses allow users to visualize the fire scenario while moving around using Cyberith Virtualizer ELITE 2.

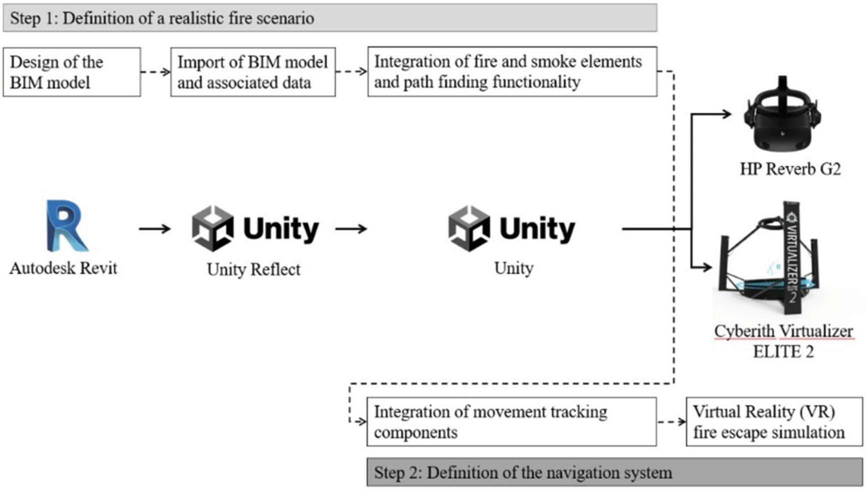

Fig. 4. The two-step approach for VR fire escape simulation definition.

4 Results and Analysis

We successfully developed a dynamic fire signage system that was implemented in a VR environment. The system is capable of changing its display of indications in real-time based on an instant input from a controlling central system, leading occupants to the nearest safe exit. In comparison to traditional signals, the dynamic fire signs were found to be easier to spot and follow, providing more certainty for the user that they are following the safe path to the exit. Overall, our study demonstrates the potential for dynamic fire signage systems to improve building safety and enhance the evacuation experience for occupants.

During this study, we created and virtually implemented a new dynamic fire sign and signage system. In this paper, we referred to the new fire sign as the FSC, which was created as a BIM object. It later served as input for the node database and pathfinding algorithm used to define the navigable spaces in the environment in which that we tested the escape scenarios. Sixteen FSCs were placed throughout the model, strategically positioned at each crossing where two or more paths intersected and where emergency exit doors were located. Each FSC was assigned an ID letter from A to P and was placed in front of each path at every crossing, providing a clear and visible indication of the direction that occupants must follow (see Fig. 5).

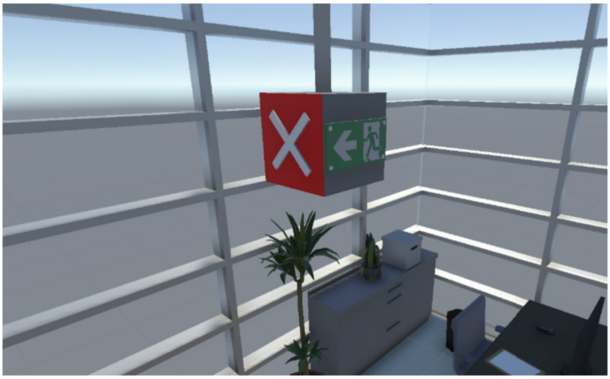

Fig. 5. Illustration of the FSC in Unity.

The FSCs had between one and four active sides, depending on their location in the floor plan and their proximity to pathways and exit doors. Each active side was capable of displaying four fire signals (stop, forward, left, and right), which were selected according to the input of the pathfinding algorithm to calculate the safest escape path. The FSCs were able to activate the correct signs that directed towards neighboring FSCs until the exit door was reached. (see Fig. 6) This approach reduced confusion and stress for occupants during an emergency evacuation, particularly as they may have difficulty making independent decisions in such situations.

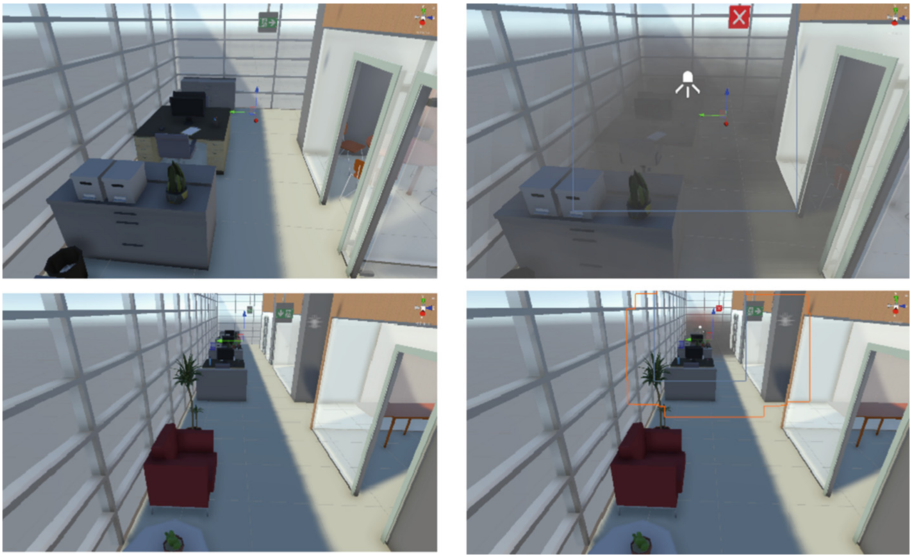

Fig. 6. Illustration of the Fire signal cube (FSC) in Unity, displaying how the FSC changes the displayed signal during fire emergency.

The pathfinding algorithm developed in this study has the advantage of being easily applicable to any BIM model without requiring significant modifications or interventions. This is due to the fact that the algorithm is based solely on the locations of the fire signs, which serve as nodes for the pathfinding process. As a result, this approach can be used in an authoring environment with minimal effort, as long as the fire signs are placed according to the evacuation principles and the exit doors are defined. This makes the algorithm highly adaptable and potentially useful in a wide range of scenarios where emergency evacuation planning is required.

5 Discussion

5.1 Conclusions

The aim of this study was to develop and implement a dynamic fire signage system in a VR environment. In this section, we present the results of the implementation phase and discuss the effectiveness of the system in guiding occupants towards safe exits during fire emergencies. The concept of dynamic fire signs has been introduced in previous studies, but its definition in standards and regulations is still inferior to conventional signage. Our system utilizes real-time input from a controlling central system to provide occupants with clear and easy-to-follow signage leading them to the nearest safe exit. The purpose of this section is to present the outcomes of the implementation and evaluate the effectiveness of the dynamic fire signage system. Additionally, we discussed the level of certainty that the system provides for users following the safe path to the exit.

Multiple human users (see Fig. 7) actively engaged in trialing the system in the virtual environment created. Various fire scenarios were simulated for each case. It resulted that the users were effectively navigated to the secure exit in all instances through the guidance provided by the FCS system.

In this case, VR proved to be an effective and successful way to experiment with fire evacuation scenarios without the need for creating a real case scene, which can be both costly and risky. By using VR technology, we created a safe and controlled environment to simulate various emergency situations and assess the effectiveness of different evacuation strategies. This approach can lead to more efficient and accurate evacuation plans and ultimately improve the safety of occupants in the event of a fire.

Fig. 7. Human users trying the dynamic fire signage system evacuation routes in the VR environment.

5.2 Limitations

Regarding the implemented pathfinding algorithm, there are some limitations and potential optimizations. Even though the implemented BFS algorithm is guaranteed to find the shortest path, there are more time-efficient algorithms that could be investigated as alternatives. For example, A* or Alpha-Beta [35] could be more efficient in terms of computing time.

5.3 Future Prospects for Implementation

Although the dynamic fire signage system in a VR environment proved to be effective in guiding the human users towards a safe exit, it is important to note that this is just the first step in implementing the system in a real-world scenario. As such, it is necessary to test the system with the participation of multiple users simultaneously and evaluate its effectiveness in guiding crowds towards safe exits during an emergency situation. This would require the exploration of dynamic escape routes and the coordination of multiple individuals in a high-stress environment. The results of such testing will provide valuable insights into the feasibility of the system and its ability to improve the safety of building occupants in emergency situations.

In order to advance the study, additional assessments will be conducted to quantify and gather data for comparative analysis with respect to a conventional fire evacuation scenario. Participants would be positioned to experience both the dynamic signage system and the traditional signage system, allowing for the measurement and comparison of evacuation times.

Since operating within a VR environment, it is imperative to assess the user experience from a human and psychological perspective, aiming to gather their feedback for evaluating the quality of the simulated environment and identifying opportunities for design enhancement. Subsequent investigations will be carried out to evaluate the intensity of the users' experience, their emotional responses, and the extent of confusion encountered. This assessment will be accomplished through meticulous external observations of their experiences and the administration of questionnaires subsequent to the tests. The collected data will be further analysed with the scope of improving the user virtual environment.

In addition, the study can be taken further to integrate it with IOT sensors and test it in real case scenarios.

Author Contributions Statement. O.B worked on the BIM model and creation of FSC, M.A worked on the literature research, J.E worked on the pathfinding algorithm, I.D.B worked on the VR simulation, E.N reviewed the manuscript, D.S and D.M supervised the development.

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