BIM-based Virtual Reality and Human Behavior Simulation For Safety Design

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The constant development of Building Information Modelling and Virtual reality in architecture and construction has gone beyond visualization and marketing in architecture to enhancing workflows of architects with assets such as immersion and interaction that assists Architects to make more informed decisions from design to construction. Using virtual reality complex decisions can be simulated and analyzed to produce iterations for the optimizing design. Recently, safety design to protect users from the risk of life has become an issue. BIM and VR for Safety Design is a beneficial collaboration for the designer to experience user safety in a virtual built environment immersively. There is a need for intensive experimentation and simulation into user-centered design safety due to the complexity of this part of the design process. The most unpredictable elements of user design safety is human behavior. this paper explores Human behavior using intelligent virtual agents in emergency situations, as this is when user safety is at highest risk in a built environment. In this paper, we explore the potential of a BIM based VR and human behavior simulation in relation to emergency situations.

Keywords: BIM, Virtual Reality, Safety simulation, Safety design, human behavior

INTRODUCTION
The development of technology in architecture such as Building Information Modelling (BIM), Internet of things(IoT), Virtual reality(VR), Augmented reality(AR) Artificial Intelligence(A.I) among others are key tools solving problems. Common problems usually generated in the Architecture engineering and construction (AEC) industry usually are from limitations to identify and analyze design problems. This creates designs from an uncertain perspective of the designer. The prevalence of uncertain data and unclear or hidden semantic information has been difficult to reconcile with the unambiguous nature of BIM parameterization (Coroado, 2015). Design problems also stem from architects uncertainties in visualization and communication of spatially uncoordinated
and conflicted assets of design.

Through a combination of BIM and VR problems generated during design can be visualized analyzed and optimized. Virtual Reality (VR) and Augmented Reality (AR) are advancements that include potential advantages from the conceptualization to facility management of the building lifecycle. VR is known as an innovation that includes the interaction and immersion to three-dimensional computer models suitable for analysis and inspection by architects (M.HOSOKAWA 2016 eCaade).

The role of architects in the Architecture, Engineering, and Construction (AEC) industry is unique because designers influence a project’s safety performance through the whole life cycle based on design decisions. Decisions made by architects in design are often uncertain especially in the initial phase which is where simulation becomes important in understanding the unbuilt environment. BIM and VR have advanced in recent years. BIM and Simulations assist architects and building engineers in experimenting and analyzing ideas, standards, and rules adequately and amend mistakes from the design stage that can become exponential later in the life cycle of the building.

Events in South Korea such as the Gyeongju earthquake, Seonmun market fire and the collapse of the Mauna resort has shown that there is a need for more analysis and experimentation in the area of evacuation disaster situations. In May 2016, South Korea implemented the Design for Safety (‘DFS’) system. Unlike the existing DFS system, the institutional meaning of ‘DFS’ in South Korea is not only to manage the safety of construction workers. As errors in the design phase of buildings can affect users later into the stages of the lifecycle of the building DFS starts in the basic conceptual design of buildings and become more important in the documentation, construction, and use of the buildings (P. Hyejin UIA 2017). Due to safety accidents, the Ministry of Land, Infrastructure, and transport has extended the concept of ‘DFS’ to user safety. User safety is at the highest risk in emergency situations which is difficult to predict and design for in any phase of design due to the diverse and numerous risk that affect users in emergencies of that affect the built environment. An indication of the importance of user safety is evident in the need for regular safety inspection in buildings.

There is importance in understanding the reaction of users in Emergency Situations. Buildings not in accordance with safety requirements or below safety standards lead to higher injuries and fatalities in emergency situations. Safety requirements are derived by choosing appropriate mitigation mechanisms to protect against the negative circumstances that constitute safety design. Previous designs depend on building code and regulations and instinctive decisions by building designers rather than rigorous experimentation and simulation. Evacuation planning demands rigorous and rational analysis of experimentation on the relationship between users’ evacuation behaviors and the physical layout of proposed buildings.

In emergency situations, user decisions need to be effective and rapid based on limited information and occasionally knowledge of the physical layouts of buildings. An example is in case of fire evacuations, Visibility is important to both occupants and rescue services. Visibility is a key factor in faster evacuation and more efficient rescue for fire services. Smoke effects cause a reduced speed in evacuation and visibility causing users to be prolonged exposure to fatal toxins. Such factors need consideration in design that goes beyond speculation and regulation (Kim J, 2004). The first step in emergency planning is to recognize and identify the hazards and determine facility vulnerabilities to emergencies. A one-size-fits-all life safety inspection checklist could not meet the needs of every facility. A basic knowledge of life safety concepts by designers can identify and abate many common types of life safety hazards but through a data-driven simulation, the ability to identify such problems is amplified.

In this paper through a procedure that combines human behavior simulation and fires dynamic simulation combined with thermal imaging used by fire-
fighters in emergency situations to analyze the relationships between humans, fire, and smoke in a Virtual built environment in an immersive VR environment. Furthermore presenting recommendations for the possibility of a real-time integration to BIM to improve workflow and efficiency.

BACKGROUND

Existing methods of fire safety design

A review of the Korean 2010 fire data shows the number of fires and casualties were decreased by -11.5%(-5,455) fires in number, civilian death tolls decreased by 25.7%(-105), civilian injuries 21.9%(-444), and property loss by +5.9%. As seen in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2009</th>
<th>Change in number</th>
<th>Change in percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of fires</td>
<td>41,863</td>
<td>47,318</td>
<td>-5,455</td>
<td>-11.5</td>
</tr>
<tr>
<td>Deaths+</td>
<td>304</td>
<td>409</td>
<td>-105</td>
<td>-25.7</td>
</tr>
<tr>
<td>Injuries</td>
<td>1,588</td>
<td>2,032</td>
<td>-444</td>
<td>-21.9</td>
</tr>
<tr>
<td>Property Loss (w million)</td>
<td>266,776</td>
<td>251,853</td>
<td>14,923</td>
<td>+5.9</td>
</tr>
</tbody>
</table>

This shows that there have been improvements such as South Korea’s advancement in research on fire safety through BIM but South Korea safety design is still limited to design adjusted to law through building codes and regulations that are validated in 2d drawing plans and 3d models that affect the built environment resulting in iterations to elements such as floor plan layouts, structure, legislation and mechanical systems with little to no consideration to emergency fire factors such as fire size, growth rate, smoke production rate and human behavior.

The normal approach to address emergency pre-planning includes preplanning drills and digital pre-planning. The preplanning drills are to record the behavior of participants (as evacuees), which usually includes the completion of a post-evacuation questionnaire to supplement and supply the results that are hard to be observed, such as perception of emergency cues during the drills (KIM, 2003). This demands a computer-aided emergency management and decision-making support. Conventionally, the fire safety assessment process is generally a paper-based process regarding official fire safety regulations.

Related Research

Safety is paramount in design and so much research has been conducted through for the safest methods to evaluate buildings. A computer simulation is a computer program that contains a model of a particular system (either factual or theoretical) and that can be executed, after which the execution output can be analyzed. Although schematically VR cannot be analyzed, there are various applications that utilized for the sole purpose of simulation provide data that can be semi-automatically inputted in VR game engine for an improved visualization of simulation (Rysanek, 2017). The challenge is, to realize the virtual simulation environment based on geometrical and material boundary conditions, to consider the mutual interaction effects of different parameters (especially the human factors) as well as the visualization of the simulated results.

Rendering and physical phenomena have become possible to study at the design stage by visual simulation and environmental simulation. As VR has become more realistic, it has allowed architect not only to visualize but experience simulations. To ensure that building designs are according to building codes and regulations many countries have created a BIM safety system promoting mandatory model checking for BIM quality including compliance with regulation while such systems have shown massive development but there is a need for human behavior in relation to design. (Kinateder, 2015).

Recent research has distinguished that the fire high risk in emergency situations has a direct connection to a delayed evacuation of facilities this can be
attributed to design factors such as complex wayfinding, lack of required egress points among others. The existing methods of fire safety design do not integrate all elements of fire design as this is a complicated, time consuming and expensive process which can create uncertainties for architects in the design stage making them vulnerable to errors that can be fatal when the building is built.

The AEC industry is dangerous by its nature of complexity and uncertainty. In the past decades, researchers have made great endeavors to improve the safety performance for the industry Decision-making for design, which previously had to rely only on designers’ experience and specifications from product manuals, can now be accurately and objectively ensured using simulation tools. A more intensive and comprehensive experimentation and simulation of fire dynamics and human behavior are necessary to solve the wicked problems an architect could encounter in the design stages that could hinder evacuation. A research showed that virtual users created through an A* algorithm applied to simulations done by students benefited them in understanding safety design in terms of egress evacuation and the student final layout plan was optimized for evacuation.

Emergency preplanning is an action plan devised as a precautionary measure before any disaster and is activated in response to major incidents only. In this paper, in an immersive 3d virtual reality environment architects can experience a firsthand look at the problems that go beyond the building layout but also other building elements such as doors, windows, furniture and material and present alternative iterations for optimization in evacuation situations. Furthermore, fast calculations allow timely feedback on new design alternatives for a project, rather than relying on speculation on the end product. Although the interoperability between Building Information Modelling and the VR game engines is semi-automatic, technological improvements of AEC VR tools such as Fuzor allow real-time visualization and workflow but lack in the tools for a more accurate human behavior and fire dynamic simulation. As seen in figure 1

**Human Behavior Simulation**

A computer simulation is a computer program that contains a model of a particular system (either actual or theoretical) and that can be executed, after which the execution output can be analyzed. Human behavior simulation exposes design errors or problems in relation to users and the building. Human behavior simulation and experimentation assist architects find the best possible solution to problems that users encounter in everyday use of buildings before it is built. (Rysanek, 2017).

Human behavior remains complex to absolutely simulate, in one tragic case, evacuees fleeing a fire at the Station Night Club in West Warwick, Rhode Island headed towards the main doors of the building while ignoring available peripheral exits. Such is an example of how rational decisions can be affected by stress and other factors in an emergency and the need for development in human behavior simulation.

Recently, computation technology allow designers to mimic reality along parameters. Computer generated simulations as a means of experimentation allow interaction between properties of autonomous agents and environmental conditions. The simulation of human behavior in buildings is as important as crash tests in automobiles.

In the context of this research, we explore not only the physical properties of the building and environment but also the properties of fire and smoke
in buildings. The process of human behavior simulation considers the impact of fire on users such as reduced visibility, impaired movement, toxicity, and stimulus (Simeone, 2013). The manipulation of virtual environments during the design process pushes designers to better perceive space, for example, its fluidity and functionality, without using 2D representations.

**Immersive Virtual Reality**

VR is known as a technology that adds the dimensions of immersion and interactivity to three-dimensional computer-generated models and offers an exploration that is not viable with the traditional form of representation.

This immersive experience allows architects to experiment with ideas compared to conventional 3D modeling tools that allows architects to only visualize models in an immersive first person. The use of immersive VR assists in analyzing building beyond floor plan layouts to other architectural elements such as windows, doors, structure, and furniture among other things in relation to positions in buildings and the efficiency of their function. (Tukera, 2013).

The effect of fires on all building elements, evacuation of users can also be analyzed in context from an immersive first-person perspective. Interactive VR also allows the simulation of wayfinding functions in and fire repellant devices such as fire extinguishers and sprinklers. Such elements efficiency can be measured in position and quantity in the building.

The cost of Immersive virtual reality has been made affordable and accessible to institutions and individuals. Virtual reality games engines are readily available for free downloads such as Unity 3D and unreal engine and the commercialization of Head Mounted Displays (HMD) like the oculus rift, HTC vive and google cardboard makes immersive architecture an everyday possibility, improving building convenience and saving lives.

**PROCEDURE**

To achieve a realistic virtual simulation. We designed a scenario of a fire in an educational facility using the Revit building sample advanced project for this simulation. This scenario allowed us to have a more detailed scope of the types of simulation to run. The accuracy of data for human and fire simulations enhances the quality of the virtual reality experience and a thermal image system increases visibility. The flow of this research starts at the modeling stage and the creation of an emergency scenario to the simulation stage for data and then visualization in an immersive environment. The overall procedure is shown in figure 2.

![Flow of procedure](image)

In this paper, we consider two fundamental elements which are human behavior Simulation and fire dynamic simulation. The Merge is analyzed in an immersive VR. This process required data that could not be random as this will generate inaccuracies. Using third-party tools simulation data was comprehensive for virtual reality visualization. The diagram below shows the process of incorporating 3rd party tools for data-driven simulation in VR.
**Fire Dynamic Simulation**

The building is modeled using the Revit BIM platform which is a BIM tool where preliminary safety checks can be made. Then exported to the PyroSim DSF simulation software. generating data to be used in a virtual reality simulation, third-party tools had to be incorporated as seen in figure 3.

PyroSim is a graphical user interface for the Fire Dynamics Simulator (FDS). PyroSim helps you quickly create and manage the details of complex fire models. Where parameters were set for, Fire source, reactions, temperature per surface area and materials.

The fire type was important we created a 1500kw burner fire with an 8m plume height with a reaction of propane gas from the reaction library. Then simulated the first 100 seconds of the fire. An analysis of the data generated from the fire dynamic simulation shows that visibility is impaired unevenly around the building from the source of the fire and visibility in the building reduced to 80% at 50 seconds into the simulation. Although we acknowledge that every second count we have narrowed our scope to the moment where the flames are its peak as this is this time evacuation is least likely and more complicated.

**Intelligent Virtual Users**

The goal of the intelligent virtual users is to evacuate the building through the nearest egress exit point considering visibility, collision with flames and other agents. The simulation allows agents unable to escape evacuate to perish as this will present a more accurate result of the simulation and elucidate consequence of poor design in disasters.

In order to generate data for our Intelligent goal driven agents we needed two main inputs 1) distance traveled and 2) speed, rather than random or uniform default values generated by default game engines. To generate the data for human behavior simulation using Oasys mass motion we imported the model and simulated an evacuation of the building. The simulation was conducted for 100 agents evacuating the building in 4 minutes and the data of each agent showing desired speed, distance traveled, agent ID, Exit is exported in CSV. File format. In a spreadsheet, we plot the speed of all agents according to speed and distance traveled. The simulation in Oasys mass motion is shown below in figure 4.

The data generated in mass motion is primarily a uniform evacuation agents. This simulation data cannot comprehensively be analyzed in relation to factors like fire and smoke which are parameters that can
be programmed based on the output data generated from FDS simulations in a game AI.

In unreal engine through code language visual blueprint scripting, we create game AI whose end goal is to evacuate the building to a safe location and make decisions based on a behavior tree. As seen in figure 5.

![Game AI behavior tree](image)

The speed of the various agents generated from the mass motion simulation is applied to the intelligent also the game AI is programmed to avoid areas of intense fire and smoke generated from the fire dynamic simulation through a collision system of unreal game engine. The fire completely blocked one of the egress exits so we blocked the exit through collision.

For this paper, we considered access to egress point as the main factor. Due to temperature and smoke patterns, three categories of accessibility perimeters were set to absolute, low, moderate and high. The combination of human behavior and the fire behavior in a virtual built environment is analyzed through these criteria. Collision set according to accessibility parameters differ from the simulation in mass motion as that was a uniform evacuation that did not factor fire dynamics. Speed ratio generated from mass motion can be seen in figure 6.

**Thermal Imaging**

Thermal imaging can be achieved using a concept of heat mapping. Heat maps can be created for the entire environment and made to track the movement of certain agents. The temperature and smoke patterns were represented to a spectrum. The spectrum was used to show the heat levels that was generated from the previous simulation in pyrosim and a combination with an infrared spectrum to visualize smoke patterns.

Heat mapping in unreal engine works similarly to infrared which is invisible to the human eye and works both indoors and outdoors similar technology is used in thermal imagining cameras (TIC) to identify patterns that exist in fires that will be oblivious to both the architect and firefighter. Fds systems use a similar concept that represents fire on spectrum base so we apply the same system in unreal engine to view what is usually uncertain due to poor visibility in a case of excessive smoke to our design.

Environmentally, Heat mapping in unreal engine works similarly to infrared which is invisible to the human eye and works both indoors and outdoors similar technology is used in thermal imagining cameras (TIC) to identify patterns that exist in fires that will be oblivious to both the architect and firefighter in a real-life situation fire. The environmental and heat map maps present a more certain tendency of both the user and the building in relation to the fire. As seen in figure 7.

![Virtual simulation in thermal image mode](image)
The immersive VR combines 3D game combines the fire dynamic simulation and human behavior in an immersive. The interactive system that allows the user to experience evacuation from all egress points. As most egress points suffer from bottlenecks and reduced visibility due to unpredictable behavior of humans in an evacuation situation and teleport through the virtual building to give feedback on design changes to building elements can be optimized to improve visibility and evacuation movement.

The simulation presented that the main egress point was not accessible due to fire patterns the exit closet to the flames and with on the shorter corridor had more reduced visibility as seen in figure 8. and through a teleporting system the user can navigate and analyze all design assets that go beyond layout.

LIMITATIONS AND DISCUSSION

Limitations

In a case of fire, fire behavior does not only compromise the elements mentioned in this paper but it mainly affects the structure and building materials. A report on the Wooshin golden suits fire in Busan South Korea showed that material was a contributing factor to the spread of the fire (Kim Y, Fire and science technology journal vol 30). The current game technology does not allow explicitly allow us to go in-depth data driving structural integrity or material simulations. In the emergency, most situations compromised structure leads to fatal either by direct contact or as a barrier to the egress point. This presents
a gap in knowledge of how structure reacts to disaster factors. We are aware of the complexities that evolve structural integrity simulations and the lack of technology for such complex simulations. We aspire in the future to incorporate structural integrity to our simulation as this will be a step closer to reality in a case of fore evacuation safety. Despite VR and AR potentials, there are still difficulties which withhold their use in AEC.

**Interoperability to BIM**

In the course of this research, one key challenge that stands out is the complexity of achieving realistic VR fire simulation. Present industry practice typically utilizing multiple models independently require consuming efforts in maintenance, updating, and coordination. (Valande, 2008).

Interoperability of software has emerged with substantial improvements in recent years, permitting some exciting developments to aid and assist designers in considering alternatives and identifying advantageous design decisions. The few AECVR tools are most viewers with only limited capabilities for functions like clash detection, foliage, and navigation. Future AEC VR platforms would be a more effective tool if safety simulations for fire, earthquakes, and other unforeseen disasters can be simulated. The Key to interoperability of BIM and VR simulation systems will need to incorporate 1) Computer language programming APIs 2) IFC support system.

Computer language programming APIs that link directly to VRBIM platforms similar to the dynamo computational design technology are needed to direct link VR simulation to BIM tools.

Through a combination of computer programming and a creation of simulation libraries for human behavior and emergency, simulation will ease the workflow and make safety design more appealing for architects. Although most architects will need to learn some form of computational programming this is a more feasible option than simulation through various third-party tools. Through computational programming, there is a possibility to create a holistic simulation API that links directly to BIM and allows real-time editing and other simulations such as energy, security and structure integrity among many other possibilities.

An IFC Support that will solve the information gap especially schematic information required for higher accuracy of simulations. In the AEC domain, the first step towards a computerized process and information interoperability has been developed in 1999 with the development of the IFC. As IFC is an internationally recognized standard this will enhance collaboration in the AEC industry through Virtual reality. The current game engines only support geometric information from which generation of documents, statistical analysis and information are not available. IFC supported VR systems will provide schematic data that could be analyzed virtually. (Wang, 2014)

**Big Data**

Some human behaviors during an evacuation have not been sufficiently understood and require further study to build a connection between the fire evacuation and fire safety engineering. Further increasing this complexity is the non-deterministic nature of human behavior itself, which is heavily context-dependent (on such aspects as culture, education, role and dynamics in the society, customs, and beliefs), due to which every human being behaves very differently from others given the same event and same built context. There is a need for visualization of not only models in architecture but also Data. Data visualization has been shown to support highly abstract multi-dimensional analyses. Many researchers look to visualization to support exploration of large datasets. Through a convergence of big data and Virtual reality, simulations can be done based on data generated from real-world situations of fire histories, drills, regulations. This makes design decisions more vivid for architects.
CONCLUSION
Our analysis of this research concludes that design elements that affect building safety are beyond the layout of the building. Uncertainties of the relation of building elements to human behavior in evacuation situations should be minimized as much as possible and visually analyzed to present various design iterations and alternatives presenting the best possible solution for safety.

Fire design entails various uncertain elements and should not be limited to building codes and regulation or intuition. Experimentation of the dynamics of fire and smoke in a virtual environment showed areas of the building that will be most affected. This allowed us to make design changes that assisted in a faster evacuation design.

Virtual reality technology is still semi-automatic, to generate the required data to create a virtual fire with realistic parameters and intelligent agents third-party tools were utilized. For future fire simulations, a real-time API with the possibility for VR simulation with human behavior simulation will be more interoperable, making workflow more convenient accurate and suitable for safety optimization design.

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