Generating 3D data, simulations, and geovisual interfaces for 21st century risk assessment and communication in multilevel space

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Abstract

Modern methods of spatial data capture, analysis and representation signify new opportunities for emergency managers to reduce the risk of and increase the resilience to natural and manmade hazards. This thesis explores the development of a progressive emergency management strategy in a complex institutional space, combining the spatial veracity of GIScience with an innovative approach for simulating and communicating emergency egress. The impact that spatial resolution and representation have on emergency evacuation calculations is examined in an analysis of 2D and 3D GIS based network analyses, and 3D game-engine based simulations. The implications of space are further examined in situated mixed reality simulations that enable the visual analysis of virtual evacuees in real-world spaces. Finally, this research introduces mixed reality geovisualizations of multilevel space as a method to communicate evacuation plans and increase locational cognizance. These interfaces challenge the status quo and encourage a 21st century approach to emergency management.

Keywords: GIScience; 3D geovisualization; emergency management; evacuation simulation; mixed reality; situated analytics

I would like to dedicate this thesis work to my wife, Heather, who provided endless encouragement throughout this journey.

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Chapter 1. Introduction

1.1. Overview

Emergency management and evacuation planning are key activities that can help institutions save lives in the event of an emergency. However, simply having a plan does not guarantee safety or increase resiliency, and the ‘plan’ is not necessarily the correct one, especially if not everyone is aware of what that plan is. For institutions at the forefront of public safety, emergency management has evolved into a proactive process in which the risks associated with all potential hazards are prepared for and mitigated, and emergency response and recovery plans are hypothesized, tested, and enacted in real-world training exercises. Emergency planning is now considered vital for institutions that wish to mitigate the impact of disasters, recover from them in a timely manner, and in the event of an evacuation, ensure everyone remains safe (Naghdi et al. 2008). Emergency exercises can help raise awareness regarding the potential risks associated with a disaster, and may provide valuable insight into the strengths and shortcomings of an institution’s emergency plan. Regrettably, they are expensive, time consuming, disruptive, lack the physical and emotional stress that accompanies a genuine emergency, and are often taken lightly or ignored. Geographic information systems (GIS) and advanced 3D geovisualization technologies provide opportunities to evaluate risk perception and risk assessment, simulate emergency conditions, enact multiple emergency scenarios, and systematically test emergency plans without the temporal and capital overhead associated with real-world emergency drills (Gwynne et al. 1999). At the same time, there is much work using GIS, that does not critically evaluate how well digital data, models, and analyses match the nuances and complexities of real-world, three dimensional spaces, spatial and temporal dynamics, and their potential to change unexpectedly.

Some of the first computer models that were developed to assess the performance of emergency procedures used architectural drawings and mathematical models. The excessive number of equations that these models required to simulate human behavior produced frequent problems and the results were often considered unreliable (Shih, Lin, and Yang 2000). Since then, progress in 3D game engine technology has produced platforms that allow for non-traditional spatial analyses, combining the principles and products of GIS with 3D game engine functionality, including artificial intelligence (AI) based simulations. These virtual sandboxes provide a platform for emergency managers to simulate the response to countless emergency scenarios without the overhead of real-world exercises. In addition, they offer methods of spatial representation that preserve the dimensionality of real-world spaces, support structurally three-dimensional analyses, and enable forms of analytical visual communication using interactive, queryable 3D spaces. Together, these characteristics deliver 3D representations and analyses that can not only be viewed and queried, but can also be experienced across many perspectives and scenarios. This in turn has major potential implications for risk communication and spatial cognition.

Effective methods of communication are an essential component of improving risk awareness and resiliency. For complex urban landscapes involving intricate building designs and elaborate transportation networks, that communication can become problematic, as the cognitive overhead required to connect spatial information with the real-world landscape is difficult. In times of crisis, that process becomes even more onerous. Modern technology offers a new, non-traditional, and multidisciplinary approach to visualizing, simulating, and communicating the intricacies of spatial problems (Shih, Lin, and Yang 2000; S. P. Smith and Trenholme 2009; Li and Giudice 2012; Lonergan and Hedley 2014), enabling simulation, data processing, and analysis within a single digital platform. The same technology applied to the assessment of risk can also be used to directly communicate that information to the public, promoting enhanced comprehension through a process of interactive sense-making (Lonergan and Hedley 2015).

1.1.1. Scope of this work

In this thesis, I present a series of geovisualizations developed to assess emergency evacuations, and communicate the evacuation plans, of multilevel buildings at Simon Fraser University (SFU). The complex and dynamic nature of built environments, and the physical objects within them, generate several challenges for traditional methods of egress analysis. I highlight these challenges in a comparative analysis of the evacuation estimates from 2D and 3D GIS based network analyses, and game-based simulations equipped with artificial intelligence (AI) enabled evacuees. I then use mixed reality (MR) as a method to overcome the difficulties associated with representing real-world features in virtual environments, bringing virtual evacuees into the real-world for situated visual analysis in real spaces. Lastly, I present a MR interface designed to promote locational awareness and communicate the evacuation procedures within multilevel spaces.

With this research, I hope to offer emergency managers a collection of assets that allow them to not only assess human movement, but to develop informed evacuation behaviors and increase emergency preparedness in institutional space. In many instances hazards are inevitable; therefore, it is imperative that emergency managers have the tools that enable effective and efficient emergency management measures that educate and inform those at risk. Through my analysis of emergency planning, simulation software, 2D and 3D network analysis, 3D modelling, and geovisualization design I hope to produce a workflow that helps mitigate that risk.

1.1.2. Related research

Emergency preparedness and resilience have become a hot topic, as extreme natural hazards are impacting larger and previously unaffected geographic areas, and greater urban density is perpetuating the problem of efficient evacuation. Furthermore, social threats such as school shootings and terrorist activity are becoming more prevalent. A call for emergency preparedness is not to be taken as alarmist, but rather to raise awareness and alert society that careful consideration of the risks and the response to them can help save lives. AI simulations and mixed-reality visualizations are examples of approaches that researchers have taken to improve emergency preparedness and build risk resiliency.

Artificial Intelligence based evacuation simulations provide a platform for testing the risk perception data that has been collected for a given location. These simulations allow researchers to conduct full scale evacuations, based on the expected social behavior of a population, without the disruption that many relate to emergency exercises. In essence, they are a conceptual sandbox for exploring evacuation theories, emergency plans, and what-if scenarios (Torrens 2015). While traditional evacuation drills would provide similar information, they are usually only performed once (Gwynne et al. 1999), or on an infrequent basis; however, virtual simulations allow for unlimited repetition. AI simulations have, to date, been developed on the margins of GIScience, and more frequently, evolve outside of it. As 3D engines and AI have matured, there is a need to develop and advance 3D representation and 3D simulation.

Geovisualization is the term used to explain a multifaceted field involving the visual exploration, analysis, synthesis, and presentation of geospatial data (Slocum et al. 2001; Kraak and MacEachren 2005). Geovisualization combines the methodologies from cartography and GIScience with the technologies developed for GIS, image processing, computer graphics (including game development, animation, and simulation) (Bass and Blanchard 2011), and mixed reality (Lonergan and Hedley 2015). The objective is to provide new ways to visualize geospatial problems, thereby revealing the complex structures of, and relationships between, geographic phenomena (MacEachren and Kraak 2001). As they relate to emergencies and hazards, geovisualizations have the potential to influence risk perception and the communication of risk, and could improve disaster mitigation, preparedness, response, and recovery (Bass and Blanchard 2011).

Geovisualizations can be applied to emergency preparedness using an array of interface technologies. Each of these interfaces is situated somewhere along the “Reality-Virtuality Continuum” (RVC) that was first introduced by Milgram et al. (1994) to help classify the relationships between an emerging collection of visual display systems. At one end of the continuum there are real environments (RE); any environment containing exclusively real world objects that are viewed either in person, or using some form of video display (Milgram et al. 1994). At the other end of the continuum there are virtual environments (VE); a VR environment that consists solely of virtual objects that are viewed using a video or immersive display system (Milgram et al. 1994). Between these two extremes lies mixed reality (MR); any environment containing a combination of real and virtual content. The MR environment can be further subdivided according to the proportion of real and virtual content. Augmented reality (AR) environments are primarily real spaces supplemented with virtual content, and augmented virtuality (AV) environments are primarily virtual with supplementary real world content (Lonergan and Hedley 2014; Hedley, 2017a).

The application of these technological interfaces to emergency management has the potential to transform the way in which we prepare for emergencies; not for their novelty, but for what they allow the user to visualize, how they allow them visualize it, and how they help the user comprehend the spatial phenomena at hand. By applying multiple methods of visualization to emergency management the user is better equipped to appreciate the phenomena, perhaps shedding light on that which may be overlooked or exposing that which cannot be seen. Furthermore, VEs can be employed to expose users to emergency based scenarios that would be too dangerous, or unethical, to experience for real, and MR environments can be implemented to help the user reify abstract phenomena in real space.

1.2. Research problem

Due to the infrequent nature and rapid onset of disasters, many people do not comprehend the physical dimension, speed, or severity of these events, nor do they possess the experiential knowledge that enables them to respond appropriately during an emergency. Consequently, apathetic attitudes prevail, and everyone from emergency managers to regular citizens can be left unprepared. There is an opportunity for geovisual environments that offer experiential learning, but that also provide the capacity for spatial analysis and visual communication of emergency related information from a variety of perspectives.

The series of earthquakes that impacted Christchurch, New Zealand in 2010 and 2011, and the experiences of the emergency management team at the University of Canterbury, serve as an example of the need for proactive emergency management. Although the university had an emergency plan in place, there was little engagement by senior management and other university citizens. Reports show that moments after the earth first shook, many appeared unaware of the dangers and were seen walking aimlessly, texting, and paying little attention to their surroundings (Seville et al. 2012). An emergency plan is not in itself, a means to an end.

There are many striking similarities between Simon Fraser University and the University of Canterbury. Both institutions are of a similar vintage and contain many architectural parallels; both are near major fault lines; and both suffer (or suffered) from a lack of interest and seriousness of purpose in regards to emergency management. The University of Canterbury restructured its emergency management culture because of the lessons learned from the devastating events of 2010 and 2011; SFU and many other institutions would be wise to learn from the experience of others.

1.3. Research questions

The following research questions form the foundation for this thesis.

1.3.1. Existing practice

- How is risk quantified, analyzed, and communicated in institutional settings? Is there agreement on a repertoire of metrics and methods?
- Is there consensus in the research community, that these methods adequately capture, assess and communicate (in everyday and emergency settings):
    - the spatial structure of complex institutional spaces;
    - the dynamics of human movement; and
    - emergency plans of specific institutions?

1.3.2. Risk characterization and evacuation analysis in three dimensions

- How are the calculated evacuation times for complex multilevel spaces impacted by different representations of those spaces?
    - What impact do the dynamic (moveable) features of real-world environments (e.g. doors, trash bins, tables) have on evacuation simulations and GIS based egress analyses?
- How do dynamic crowd simulations and 2D/3D GIS characterize emergency scenarios and risk within institutional space?
- Can mobile augmented reality applications connect virtual evacuation simulations with the real-world environments they characterize?
- In what ways does a 3D, versus a 2D, approach to risk characterization have the potential to impact risk management? Including, an ability to:
    - represent the geometry and topology of complex institutional spaces;
    - quantify and analyze risk;
    - simulate dynamic emergency scenarios involving people moving through institutional spaces to safety;
    - effectively communicate complex spatial relationships and human dynamics in multilevel spaces?

1.4. Research objectives

The objectives of this research are to:

- Assess the current body of research literature related to the use of GIS, simulation, and artificial intelligence for risk and emergency scenario analysis.
- Assess the differences in the capabilities of GIS, simulation and AI to represent and analyze risk in complex institutional spaces, in 2D versus 3D.
- Develop and demonstrate the potential of 3D capture, representation, analysis, simulation, and visualization interface workflows to deliver a 21st century 3D evacuation analysis and risk communication toolset.

1.5. Thesis organization

This thesis is organized into five chapters. Each of the three chapters following this introduction is written as a stand-alone journal article for submission to peer-reviewed journals. Collectively, these chapters address the research questions and objectives outlined above, and provide a framework for progression towards 21st century emergency management.

Chapter 2 presents a collection of geovisual analytical environments that were developed to quantify the effect of different spatial representations on emergency evacuation calculations. While human behavior is central to many simulation software systems, I argue that spatial representation is a critical component of these calculations that is currently overlooked. Built spaces have complex and dynamic features that are inadequately and improperly represented by the attribute tables of GIS shapefiles or the prescriptive scenarios of other simulation systems. In this chapter I use 2D and 3D GIS, Unity (game development software), 3D modelling, and photogrammetry to highlight the impact that spatial representation has on egress calculations.

Chapter 3 outlines the workflow behind a collection of innovative mobile MR applications for the visual analysis of simulated human movement in real-world environments. While computer based simulations are important for egress analyses, they often contain abstracted representations of the spaces they evaluate. The simulations presented in this chapter demonstrate how MR simulations built in virtual spaces can be situated within real space, allowing emergency managers to visually analyze simulated human movement against the features of the real-world.

Chapter 4 presents the final component of this thesis research – to demonstrate the potential of 3D evacuation communication using a set of working MR prototypes. The evacuation plans of multilevel buildings generally provide a 2D snapshot of that space, asking the reader to connect that snapshot with their mental representation of that space. However, mental mapping in complex multilevel spaces is inherently difficult, often resulting in incomplete or misaligned mental maps. In this chapter I present a workflow for promoting spatial awareness with AR geovisualizations that provide contextualized emergency evacuation information.

The concluding chapter contains a discussion on the significance of the research presented in the preceding chapters, and suggests topics therein that require further examination.

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Chapter 2. Modelling evacuation in institutional space: linking 3D data capture, simulation, analysis and visualization workflows for risk assessment and communication[1]

2.1. Abstract

This paper presents exploratory research to develop new workflows that address the challenges of adequately capturing the geometry and topology of complex institutional spaces, the analysis of prescriptive evacuation plans, and the simulation of human movement and behavior in emergency scenarios. We present a collection of geovisual analytical environments that were developed to permit new ways to view and assess risk, evacuation, and human movement. Part of this research considers how different approaches to the representation of complex institutional space, using 3D capture technologies at multiple resolutions, (or derived from conventional formats, such as building plans) have implicit advantages or liabilities in the analysis of risk and human evacuation. We combine 3D data capture methods with GIScience theory, 3D game engines, 3D evacuation simulations and spatial analyses that address the variability of campus populations, and draw upon 3D modelling and photogrammetry for the assessment of real world features in digital space. The outcome of this research demonstrates agile workflows that address emergency planning requirements, but could also enable enhanced visual analysis and interactive learning by all campus citizens. Furthermore, this work reveals key considerations and limitations associated with the dynamic nature of evacuation events and the static environments in which they have been simulated.

2.2. Introduction

Evacuation planning is an important element of the emergency management process. In this paper, we demonstrate how two-dimensional (2D) and three-dimensional (3D) Geographic Information Systems (GIS) approaches to representation,

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[1] A version of this chapter has been accepted to *Information Visualization* under the co-authorship of Nick Hedley.

analysis and simulation of evacuation in complex institutional spaces may enhance or impede our ability to detect, interpret and quantify risk.

We compare the results of 2D and 3D network analysis to those of dynamic, game engine-based environments built with artificial intelligence (AI) based agents and spatially rigorous 3D models. Through this, our goal is to highlight the risk associated with simplified representations of the built environment and the implications they have for the representation of institutional space, human movement potential through it, and evacuation performance.

A simplified representation of the real-world is one that fails to account for, or capture, the complexities of the built environment. These ‘sterilized’ representations account for the buildings structure, but do not include the contents which influence peoples’ movement. In an age of 3D scanning and capture, it is all too easy to assume that the latest high resolution scan results in the ‘best data available’ or the ‘best 3D capture’ of 3D space. It is imperative to remember that the potential of high resolution data is critically reliant on sophisticated modeling specifications and the conceptual architecture that underpins them. Therefore, the spatial resolution of data capture is only part of the picture.

Emergency exercises and computer based evacuation simulations are commonly used to gauge the performance of evacuation plans. While emergency exercises can help raise awareness surrounding the potential risks associated with a disaster, and may provide valuable insight into the strengths and shortcomings of an institution’s emergency plan, they are expensive, time consuming, disruptive, and they lack the physical and emotional stress inherent with real disasters. Furthermore, prescriptive, top-down emergency plans may not match the on-the-ground perception of risk by citizens (Hedley 2012). GIS based analyses and 3D geovisualizations provide an opportunity to evaluate risk perception and risk assessment, simulate emergency conditions, enact multiple emergency scenarios, and systematically test emergency plans without the temporal and capital overhead associated with real-world emergency exercises (S. Gwynne et al. 1999).

Geovisualizations are powerful tools that enable the visual exploration, analysis, synthesis, and presentation of geospatial data (Kraak and MacEachren 2005). As a field of research, geovisualization combines methodologies from cartography and Geographical Information Science (GIScience) with the technologies developed for GIS, image processing, computer graphics (including game development, animation, and simulation), and alternative realities (Bass and Denise Blanchard 2011). The objectives of geovisualization (and, for that matter, geovisual analytics) is to provide new ways to visualize geospatial problems, revealing unknowns, the complex structures of, and relationships between geographic phenomena (MacEachren and Kraak 2001). As they relate to emergencies and hazards, geovisualizations have the potential to deliver new ways to combine analytical characterization with geovisual communication. These capabilities may enhance user-driven risk assessment and communication tuned to available data, thus improving disaster mitigation, preparedness, response, and recovery through improved awareness of possible scenarios and outcomes (Bass and Denise Blanchard 2011).

Due to the infrequent nature and rapid onset of disasters, many people cannot comprehend the physical dimension, speed, or severity of these events, nor do they possess the experiential knowledge that enables them to respond appropriately during an emergency. Geovisualizations and virtual simulations are well suited in enabling planners and researchers to evaluate an almost infinite set of scenario permutations using many different combinations of data; at human, institutional and regional scales. The purpose of this paper is to report work we have done to produce an analytical workflow for developing, evaluating, and communicating evacuation plans. We draw upon literature on the use of traditional GIS, non-traditional hybridized forms of GIS, and simulation software for visualizing and evaluating evacuation performance in the built environment. A collection of geovisualizations will be presented using a portion of the Academic Quadrangle (AQ) at Simon Fraser University's (SFU) Burnaby, BC campus as a case study.

In response to these challenges, this paper aims to assess the variable capabilities that 2D and 3D GIS, simulation software, and game based AI hold to represent and analyze evacuations of complex institutional spaces. Furthermore, we will demonstrate the potential of 3D capture, representation, analysis, simulation, and visualization interface workflows to deliver a 21st century 3D evacuation analysis and risk communication toolset. This research has four core objectives: (1) develop a workflow for multidimensional evacuation analyses; (2) quantify the impact of varied representations and characterizations of space; (3) quantitatively express the influence of dynamic spaces on computer simulated evacuations; (4) demonstrate how geovisualizations are a means to support informed decision making.

2.3. Previous work

The research presented in this paper evolved from an initial curiosity regarding the emergency evacuation procedures, and the communication of those procedures, at SFU. That enquiry was incited by observed inaction in response to fire alarms, and the apparent lack of emergency exercises involving the student body; both of which, raised questions about planning for evacuations and instituting plans without practical experience. As geographers, it was evident that there was a distinct spatiality to the problem, and as such, it could benefit from the science and systems behind GIS. While human behavior is undoubtedly a key component of evacuation research, and remains the focus of much simulation research, SFU's campus population is primarily transient, and therefore, attempts to generalize the fluctuating populations behavioral characteristics are extremely difficult, and lay beyond the scope of this research. However, the built environment remains comparatively constant, and plays an integral role in the deterministic movement of people on campus. In the following sections, we comment on the use of GIS, simulation software, and serious games in emergency management, focusing specifically on the ways in which real spaces are represented and visualized in digital environments.

2.3.1. GIS and emergency management

GIS has become an important component of many emergency management operations. These GIS based intelligent emergency response systems (GIERS) emerged after the 9/11 disaster due to the demand for a singular system containing all of the infrastructure in New York's downtown core (Kwan and Lee 2005). However, these systems are capable of much more than simply organizing, storing, and displaying spatial data for response efforts. The functionality within a GIS enables spatial analyses and the exploration of spatial data in new ways (Dash 1997). A GIS can be used to identify, classify, and prioritize hazards, and as such, has become an important tool for risk assessment (Armenakis and Nirupama 2012). GIS can also be used to evaluate evacuation routes (Shimura and Yamamoto 2014; Naghdi et al. 2008), to improve pedestrian flow in urban environments using agent based modelling (Shelton 2012), and has been used as the basis for 3D evacuation simulations (F. Tang and Ren 2012). Therefore, a GIS serves several functions for emergency management, of which we focus on its capacity to assess and visualize human movement.

The scale at which natural and manmade disasters can occur varies greatly, yet much of the literature documenting the use of GIS in disaster management and evacuation planning focuses on large scale evacuations. While this may be the traditional application, the same tools can be applied to small scale (e.g. within buildings) environments (F. Tang and Ren 2012). Many report on the movement of vehicles, the ability for responders to access victims, the movement of people from one block to another, or from areas of danger to areas of safety (El-hamied and Saleh 2012). A GIS, while it is capable of network analyses, often serves as a supplement to simulation modelling software as part of a spatial decision support system (de Silva and Eglese 2000). As such, it is suggested that GIS is underutilized for evacuation planning and execution, and should serve a more central role (Wilson and Cales 2008). Regardless of the role it plays, the GIS is often touted for its capacity to visualize spatial data.

The above-mentioned applications for GIS in evacuation planning were all 2D, yet the nature of disasters and the landscapes they impact are 3D. The apparent lack of GIS based human scale evacuation analyses could be attributed to the 3D nature of the problem, and the fact that given the predominately 2D nature of GIS, these analyses were not possible (Tiwari and Jain 2015). However, researchers have combined the analytical powers of a GIS with 3D-viewers, enabling GIS based 3D analyses of evacuations from burning buildings (F. Tang and Ren 2012). With a growing demand for, and realization that, 3D spatial analysis is required, GIS software now offers 3D functionality. However, that functionality is often used in combination with other 3D software, attempting to overcome the limitations with its previously touted visualization capabilities.

2.3.2. Simulation software

Evacuation simulation software differs from GIS based simulations in that their primary function is to analyse the movement of people. Studies measuring and modelling this movement date back to the 1970s, focusing either on the movement of people under normal conditions, or under emergency conditions (S. Gwynne et al. 1999). Research into emergency evacuations emerged in the 1980s, and can be categorized as those that focus on the structure and its deterministic role in human movement, or those that contain active participants that respond to changing internal conditions (e.g. fire or smoke) (S. Gwynne et al. 1999). These models are often used by engineers when calculating the evacuation time from buildings, and have contributed to the adoption of performance-based building codes that better suit the complex nature of modern architecture (Tavares 2009).

A few publications have addressed the differences between the assortment of evacuation simulation programs available. Gwynne et al. assessed the 22 models available in 1999, Kuligowski and Peacock reviewed 30 models in 2005, and then Kuligowski, Peacock and Hoskins reviewed 26 models in 2010. Each review assessed the models based on a collection of factors (e.g. availability, purpose, movement, visualization), allowing for a quick comparison, and proper application, of the model. While a full review is beyond the scope of this paper, it should be noted that over the years there was marked increase in the complexity of the models, with a growing emphasis on human behavior and continuous transportation grids, and a greater diversity in outputs – almost all of which allowed for 3D visualization of some form (Kuligowski, Peacock, and Hoskins 2010).

The accurate representation of human behavior in evacuation modelling appears to have become the holy grail of the field. The onus placed on evacuation models by performance-based building codes demands that these calculations accurately represent the reality of human movement. However, representing the complexity of human behavior in computer based code is difficult, and any model is simply an estimate based on available data and theories, and relies heavily on the developers knowledge and judgement (Gwynne, Hulse, and Kinsey 2016). While these models undoubtedly have their place, they could soon be challenged by models which have gamified these scenarios, drawing upon computer game development software that allows real people to control the evacuees within the computer model.

2.3.3. Serious games

The application of game based technology to emergency management is driven by the realization that it is an experiential process. Traditionally, emergency management literature stresses the importance of a cyclical process of mitigation, preparedness, response, and recovery (Naghdi et al. 2008; Bass and Denise Blanchard 2011). However, the experiences of the University of Canterbury, which was devastated by a series of earthquakes in 2010 and 2011, have uncovered the importance of risk identification, reduction, readiness, and review (University of Canterbury 2014). These actions include several hands-on, real-world training exercises. Conducting these experiential activities involves a significant financial and temporal investment; however, serious game-based geovisualizations provide an opportunity to reduce that overhead while enabling the experiences that foster new knowledge.

Serious games have been developed for a range of disaster scenarios, with varying degrees of sophistication. Researchers have developed virtual environments (VE) that teach children the importance of fire safety and allow them to experience an immersive, head mounted display (HMD) based simulation of a structural fire (Smith and Ericson 2009). Others have used surround displays and HMD based interfaces to test way-finding procedures or to evaluate the effectiveness of emergency signage (Meng and Zhang 2014; C.-H. Tang, Wu, and Lin 2009). These game based scenarios serve several purposes, including the testing of evacuation plans, the visualization of disaster scenarios, and training individuals through experiential learning environments.

These experiential learning tools can be taken into the field, as the platforms on which these games are developed allow the developer to publish them on an array of interface technologies. Current research is exploring the use of mobile technology for emergency wayfinding in real environments using mobile augmented reality (MAR). In these cases, the information from these serious games is superimposed on the real-world using location aware mobile devices such as smartphones and tablets. These interfaces allow the user to visualize evacuation information (routes, hazards, muster stations) in situ, improving their chances of survival during an emergency (Dünser et al. 2012; Tsai and Yau 2013).

2.3.4. 3D visualizations for emergency management

The quality of the evacuation analyses and the ability to comprehend the results of them, is paramount to improving our understanding of human movement in built spaces. Inherently, the 3D nature of these problem spaces necessitates a 3D approach to both the analysis and the communication of the results. While many GIS and simulation software packages now offer 3D tools, their representations of the complexities of 3D built spaces, and the dynamic processes within them, are limited.

Research into virtual geographic environments (VGEs) attempts to overcome these limitations by creating spatially rigorous 3D worlds that allow for focused analyses of human and physical processes through space and time; however, the dynamic nature of these phenomena, and the complex interactions between them, presents a serious challenge for researchers (Torrens 2015a). Some have turned to citizen science, asking the public the recreate the features of real spaces in virtual 3D environments using smartphone enabled mobile apps (Eaglin, Subramanian, and Payton 2013), while others have developed highly sophisticated VGEs that fracture 3D buildings in and effort to simulate the impact of crumbled architecture on human movement (Torrens 2015b). This new approach to modelling and simulating human movement acknowledges the variability of the problem space, and the role it plays in dictating human movement within it. Their application is no longer limited to the algorithmic analyses of building safety or egress, but can now be applied to real-world scenarios that allow first responders to simulate, and manipulate, the impact of events on human movement in real-time (Guest et al. 2014).

As the analytical capabilities of these tools increases, so to does the complexity of the results. Simply transitioning from 2D to 3D analyses of built structures creates occlusion issues when the results are presented on 2D maps. When displayed from a fixed perspective, the information in the foreground restricts or obstructs the viewer’s ability to see the information behind it. Regardless of the maps characteristics, the perspective nature of the visualizations proves problematic, and research has shown that dynamic visualizations of 3D building data are preferable (Zhou et al. 2015). However, when applied to egress analyses, these animated or manipulatable graphics present static snapshots of a dynamic process that necessitates simulations that can be manipulated in real-time.

2.4. Methodology

We have briefly introduced the use of GIS, evacuation simulation software, and serious games to emergency management. While each may be working towards a common goal, there is little evidence that they have been combined to create an experiential, as well as an analytical, workflow that can be used for emergency planning, communication, and training. The application of these methods to emergency management has the potential to transform the way in which we prepare for emergencies; not for their novelty, but for what they allow the user to visualize, how they allow them visualize it, and how they help the user comprehend the spatial phenomena at hand. By applying multiple methods of visualization to emergency management the user is better equipped to appreciate the phenomena, perhaps shedding light on that which may be overlooked or exposing that which cannot be seen.

We describe here our efforts to produce a workflow that highlights the importance of accurately capturing the geometry and topology of complex spaces, and demonstrate how these representations impact evacuation calculations. Also presented are a collection of geovisual analytical environments that were developed to provide new ways to view and assess risk, evacuation, and human movement. We combine 3D data capture methods with GIScience and game development software for sophisticated evacuation analyses that address the variability of campus populations, and draw upon 3D modelling and photogrammetry for the assessment of real-world features in digital space.

All analyses focus on the movement of people throughout the fourth, fifth, and sixth floors of the AQ at SFU. The building is a six-floor concrete structure that sits at the centre of the campus, connecting multiple buildings across multiple levels. At the centre of the fourth floor is large courtyard, with the fifth and sixth floors perched atop a series of stairwells, supports, and classrooms.

2.4.1. 2D GIS

The 2D GIS analyses were developed using Esri's ArcGIS 10.3 software. The shapefiles which represent the structure of the building were built from data provided by SFU Facilities Services, and characterise each floors footprint, classrooms and offices, centroids, hallways, and the location of stairwells. The network analyst tool was used to create a transportation network on each floor. From this, the distance from each classroom or office to each stairwell (on the fifth and sixth floors) or exit (on the fourth floor) was determined. The distance from each could be used to infer travel time according to documented evacuation walking speeds (Rinne, Tillander, and Peter Grönberg 2010).

2.4.2. 3D GIS

The shapefiles produced for the 2D analysis were converted to 3D features so that they could be incorporated with Esri's ArcGIS 10.3 3D Analyst and ArcScene software. The elevation data required for proper positioning of each floors features were collected using Trimble's R10 GNSS surveying system, providing a vertical precision between 1.1 – 3.4 cm. The stairwells on each floor were manually connected to each floors network, creating a singular 3D transportation network for the AQ. The distance from each classroom or office to the exits on the fourth floor was then calculated using the network analyst tool. Distance could then be converted to time using the data from the aforementioned report.

2.4.3. 3D modelling

The 3D model of the AQ was constructed using SketchUp 3D modelling software. The 3D structure of the building was extracted from a series of architectural drawing data files (.dwg) provided by SFU Facilities Services. Each floor was extracted in accordance with the collected GPS data. Those floors were then combined to represent the structure of the classrooms, offices, hallways, and stairwells throughout the building. The stairwells in this model are represented by ramps, as ramps mitigated the irregular AI movement that resulted from cylindrical agent colliders and stepped surface colliders in preliminary simulations, while continuing to provide flow rates indicative of real-world scenarios.

2.4.4. Photogrammetry

Photogrammetry software was employed to build the 3D structure of a conference room within the AQ. The software combined 293 images, captured with a point and shoot camera (Canon PowerShot SX240HS 12.1MP), representing both the 3D structure of the room and its contents as a 3D file. The software that was used to produce the 3D model was Agisoft PhotoScan. Photogrammetry provides a rapid and precise method of 3D data capture for simulated egress analyses in 3D digital replicas of real-world environments.

2.4.5. Serious games

These 3D visualizations require a software system with the capacity to integrate GIS data with 3D files, that represents transportation networks as contiguous 3D spaces, and that contains artificial intelligence (AI) based agents (third person characters) and 3D physics. The software that we used to accomplish this was the Personal Edition of Unity Game Engine, Version 5.3.4. This software contains the required functions within the freely available software and assets packages, and provides a wide range of platform support for visualization outputs. Scripts were written in the C# programming language.

Unity is a game engine, and as such, it was imperative that we validate its use as an evacuation simulation platform. Other studies have proven Unity to beneficial in evacuation analyses (Rinne, Tillander, and Peter Grönberg 2010). Our validation process involved a series of tests that measured the flow rate through an open doorway. The real-world width of the door is 0.85 m; thus, the model was scaled accordingly. These tests were based on the SIMULEX tests conducted by Thompson and Marchant (1995), using its flow rate formula (1), results, and the included UK building regulation values.

$$\mathrm{Q} = \frac{20}{\mathrm{w}(\mathrm{T25}-\mathrm{T5})} \tag{1}$$

Where: Q = flow rate (persons/sec)

w = exit width (m)

T_{25} = time for 25 persons to pass through exit

T_5 = time for 5 persons to pass through exit

This series of tests involved AI based agent's characteristic of the average height and shoulder width of adult males and females (http://www.firstinarchitecture.co.uk/average-male-and-female-dimensions). The dimensions of the agents are used to generate a navigation mesh, which defines all walkable areas in the model. The agents were arranged in rows of five, with the first row placed 2 m from the doorway to ensure continuous movement (as per the SIMULEX tests), and each subsequent row was placed behind the one in front of it. Our tests were influenced by the SIMULEX tests of Thompson and Marchant, but varied agent size by including agents that were either all females, all males, or a mixture of males and females, and aligned agents either facing the doorway or away from it in varying directions (Figure 2.1).

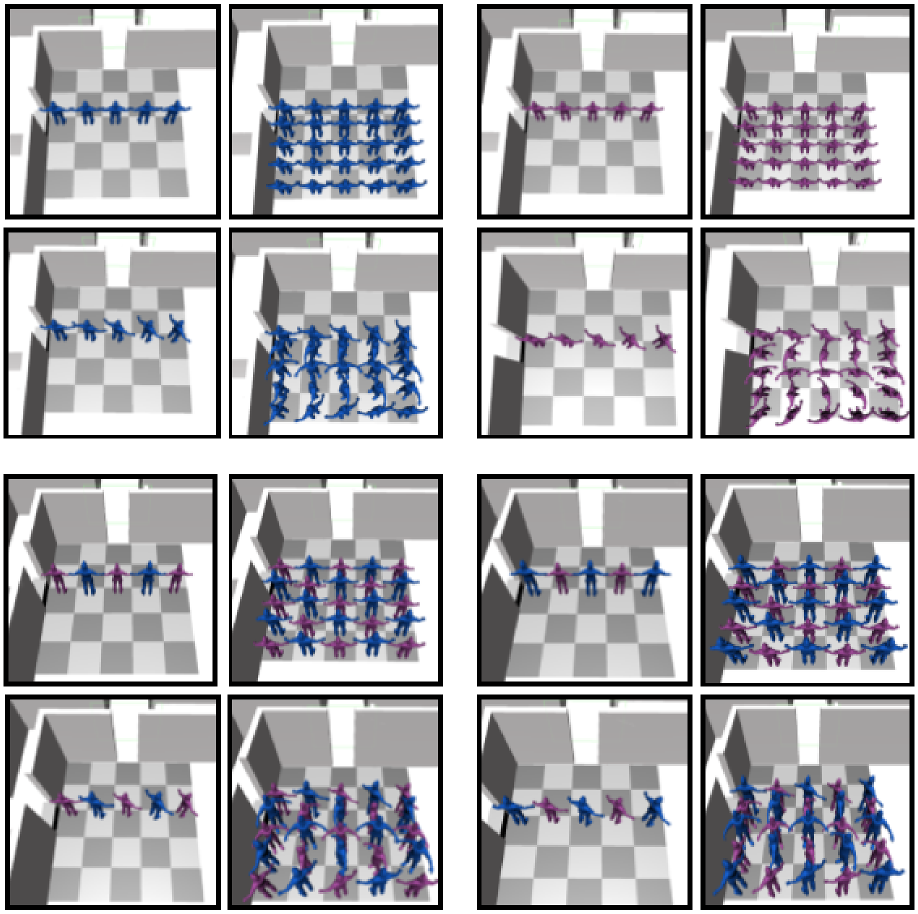


Figure 2.1 Unity Flow Rate Tests
Flow rate validation tests were conducted with sixteen different agent configurations. Agents either faced the doorway or were oriented away from it in fifteen degree increments, and were either all male (blue), all female (pink), or a combination thereof.

The results from these tests compare the Unity results to those of the SIMULEX tests and UK regulations (Figure 2.2). All further evacuation analyses were conducted with male agents facing the doorway, as the measured flow rate of 0.98 persons/second aligned with the above-mentioned models.

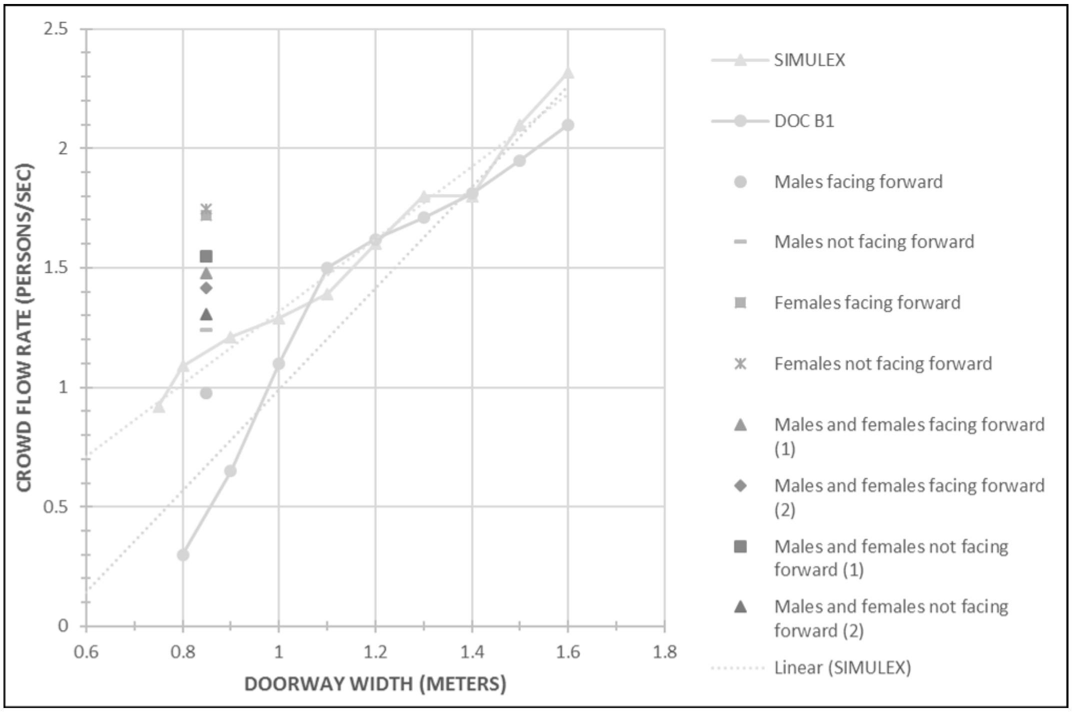


Figure 2.2 Unity Flow Rate Validation
The results of the sixteen validation tests were compared to the SIMULEX results and UK building regulations (DOCB1) to ensure optimal flow rates within our simulations. The tested doorway width matches the real-world width of 0.85 meters.

A second set of validation tests were conducted to confirm that the evacuation times calculated in Unity are representative of the actual time required to travel from a sixth-floor conference room to the nearest stairwell. Those results are presented in Table 2.1. The simulated values from the Unity test are comparable to the real-world, and are within the estimated times from GIS based network analyses.

Table 2.1 Validation Tests for Unity Evacuation Simulations

Test	Time (sec)	Speed (m/sec)
2D GIS (fast)	16.10	2.10
2D GIS (normal)	19.88	1.70
2D GIS (slow)	22.54	1.50
Unity VE	18.54	1.82
Real-world	18.73	1.80

2.5. Visualizations

This research contains a series of evacuation visualizations that explore the impact of precision of building representation on evacuation performance assessments. These visualizations begin with 2D GIS analyses of the distance from the origin (classroom or office) to the destination (exit or stairwell), and progress to 3D GIS analyses and game engine based evacuation simulations. This progression highlights how evacuation estimates vary when we change the lens with which they are evaluated.

2.5.1. 2D GIS

The 2D GIS analyses were conducted using ArcGIS, and measure the distance, and inferred time, required to get to an exit from the classrooms and offices of SFU's AQ. As the AQ is a multilevel building, some floors have direct access to the outside, and some must feed through other levels to access an external exit. Those rooms that are on the same floor as an exit measure the distance to the nearest exit, and those rooms on floors without a direct exit to the outside measure the distance to the nearest stairwell. The goal of these analyses was to achieve a baseline evacuation distance for each room, and to highlight the challenges associated with calculating evacuation distances for a multilevel building using a 2D GIS.

With the network analyst toolset in ArcMap, it is possible to calculate the distance to each of the defined destinations, either focusing on one or multiple destinations on each floor. In each case, the network consists of a series of nodes, representing the location of each floors hallways, that is used to connect the origins to the destinations. The evacuation information can be visualized using 2D maps, tables, or graphs.

In these analyses the maps characterise the evacuation distances as colored lines, with darker red hues indicating greater distances (Figure 2.3). As each map represents a single floor, viewing more than one floor at a time requires multiple maps, since the x and y location of each in geographic space is the same. This can create some difficulty or confusion for the viewer, as could the simple fact that floors five and six represent distances to stairwells and not exits. When graphed, all floors can be assessed at the same time, enabling a comparison of the distances to the closest destinations throughout the building (Figure 2.4).

Our simple network analysis of the AQ highlights some of the challenges that arise when analyzing evacuation pathways within multilevel buildings. The 2D distance to stairwell calculations for those floors above ground level, while still informative, do not represent the distance out of the building. Therefore, there is a need for network analyses which address the 3D nature of the transportation networks within multilevel buildings.

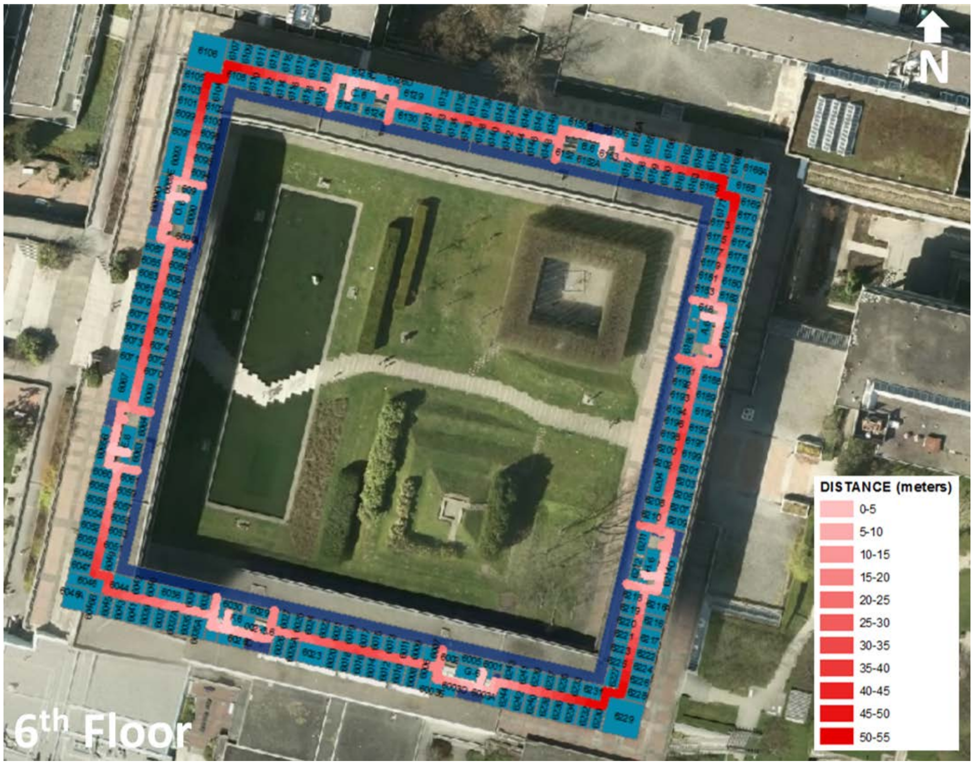
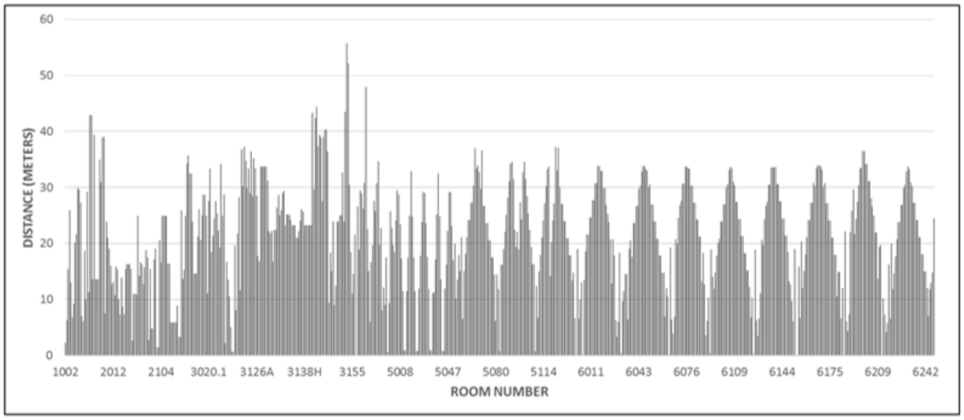
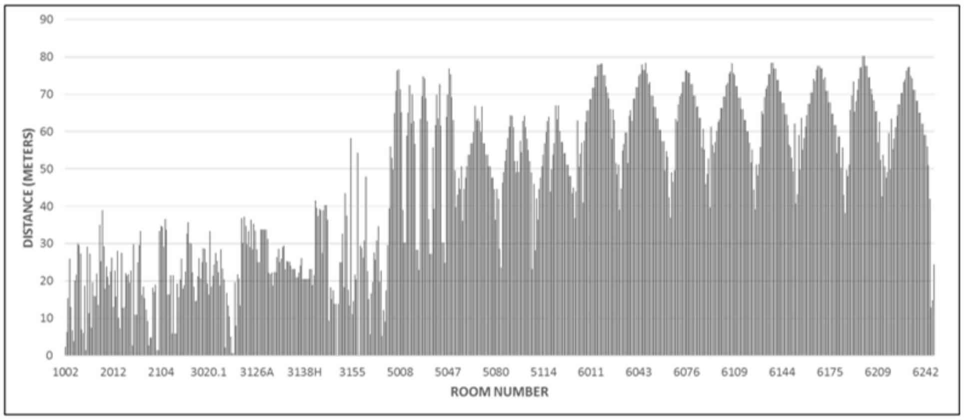


Figure 2.3 2D Evacuation Calculation
A 2D map restricts the amount of information that can be presented about a multilevel structure. This map of the distances from an exit on the 6th floor of the AQ obstructs the view of those floors below it. To create a complete evacuation map, a series of maps must be presented to the viewer, increasing their cognitive load and forcing them to align the maps in their mind.

a) 2D Evacuation Distance



b) 3D Evacuation Distance



c) 3D Evacuation Distance with Network Modification

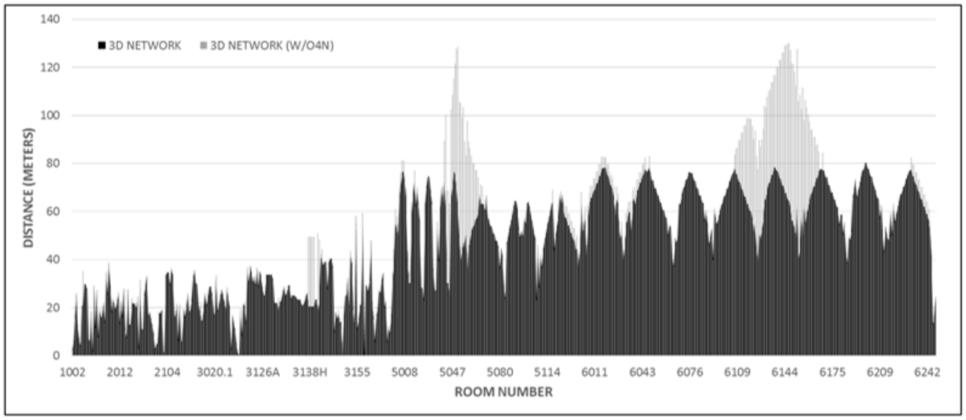


Figure 2.4 AQ Evacuation Distance Calculations

a) A graphical representation of the 2D distance from all origins to destinations within the AQ allows for a comparison of the distance between and across floors. This approach allows easy recognition of patterns and problem areas within the building. Due to the 2D nature of the data, and the 3D nature of the real-world problem it measures, this graph does not capture the true distance to an exit when floors are above or below ground level. **b)** A graphical representation of the distances from origins to destinations within the AQ using a 3D network analysis. The 3D network analysis accounts for all possible destinations within the building, not simply the 2D distance to the destinations on the same floor. When compared to 2D network analyses, 3D analyses provide higher accuracy distance measurements within 3D structures. **c)** GIS based network analysis allows the user to specify the origins and destinations to be used in the analysis. Selectively, these can be omitted from the analysis to measure the impact on the distance calculations. In this case, the northern 4th floor exits which only face the courtyard were deemed to be unsafe to exit. When both analyses are plotted on the same graph, it is evident that the removal of those destinations (W/O4N) has a significant impact for select origins in the 5th and 6th floors.

2.5.2. 3D GIS

Our 3D network analyses were conducted in ArcScene, and utilized modified versions of the 2D shapefiles used in the 2D analysis of the AQ. The 3D shapefiles are positioned within 3D space using GPS coordinates with precise elevation values, and the 3D network was constructed by connecting each floor with stairwells built in 2D and extracted to their 3D form (Figure 2.5). Using a 3D network, origins can be connected to destinations on any floor, allowing closest destination analyses to target destinations on floor numbers differing from the origin (Figure 2.6).

As in the 2D analysis discussed earlier, the 3D network analysis performs the same network calculations, only with a connected 3D network that better represents the real-world. The calculated evacuation information can be presented as maps, tables, or graphs; however, when viewed natively in ArcScene, the 3D data can be rotated to allow the viewer to explore all floors at the same time, simply changing the perspective from which they view it.

With the 3D analyses, the calculations for the fifth and sixth floors represent true distance values to exits and not simply to the closest stairwell. When presented graphically it is apparent that select origins on the fifth and sixth floors are the furthest, of any origin in the AQ, away from an exit (Figure 2.4). While this may not come as a surprise to those familiar with the buildings structure, these visualizations can help advance consciousness regarding the transportation networks connectivity, and promote further thought about that networks place in 3D space. As an example, the fourth floor exits on the north side of the AQ only feed into the buildings courtyard, whereas all other stairwells have exits to the inside and outside of that courtyard. If those singular exits on the north side were compromised (or if evacuating into the courtyard was unsafe), there is a definite impact on evacuation performance (Figure 2.4). The increased distance and time could have serious implications on the personal safety of the buildings occupants.

The GIS based analyses of evacuation performance in this study focus on the distance from the origin to the destination. While distance is of value to emergency planners, the characteristics of the network (e.g. hallway width, crowd density, presence of stairwells) along that distance, as well as the influence of other evacuees and obstacles, impacts the amount of time it takes to travel that distance. Inferences on evacuation time can be made using the reported speed of individuals during an emergency evacuation, but properly accounting for all factors in a 3D GIS, as in evacuation simulation programs, becomes mathematically complex.

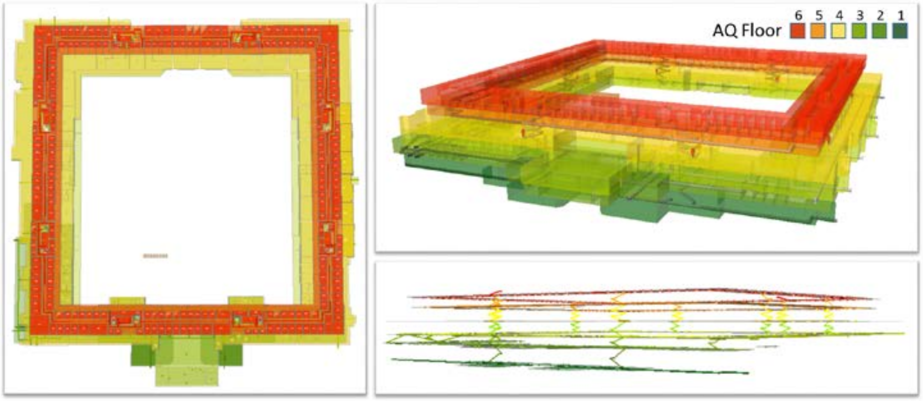


Figure 2.5 3D Academic Quadrangle
(left) When viewed at azimuth, the top floor of the AQ obstructs the view of the floors below it, limiting the amount of information that can be presented. **(top right)** A 3D GIS model of the same building allows the viewer to view multiple floors at one time. **(bottom right)** A 3D network allows for 3D GIS network analysis.

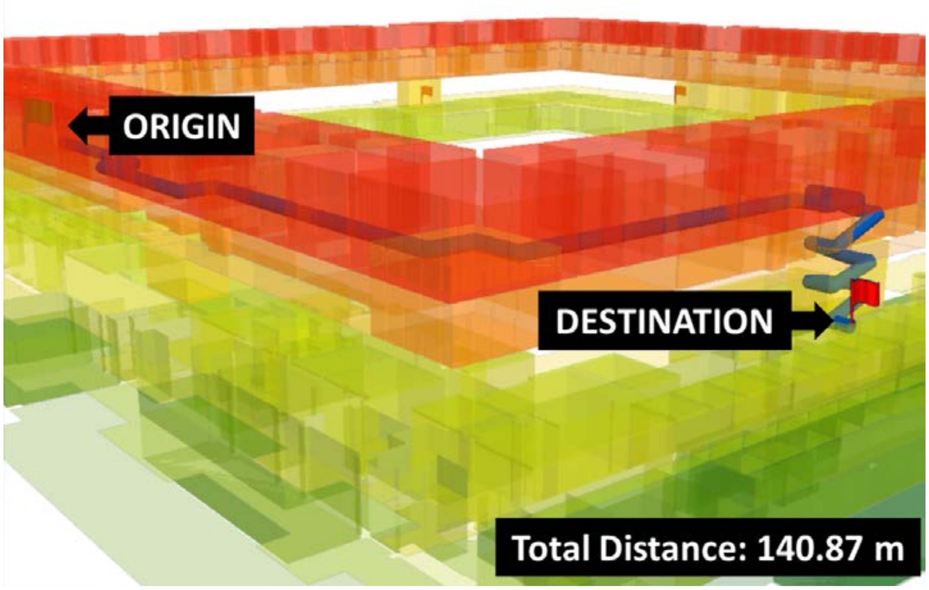


Figure 2.6 3D Network Analysis
3D network analyses allow for distance measurements on a 3D network. In this case the origin (green flag) on the 6th floor to the destination (red flag) on the 4th floor is measured and represented by the 3D blue line. A 2D analysis of the distance to the destination would not account for the 3D stairwell and would underestimate the amount of time required to exit the building.

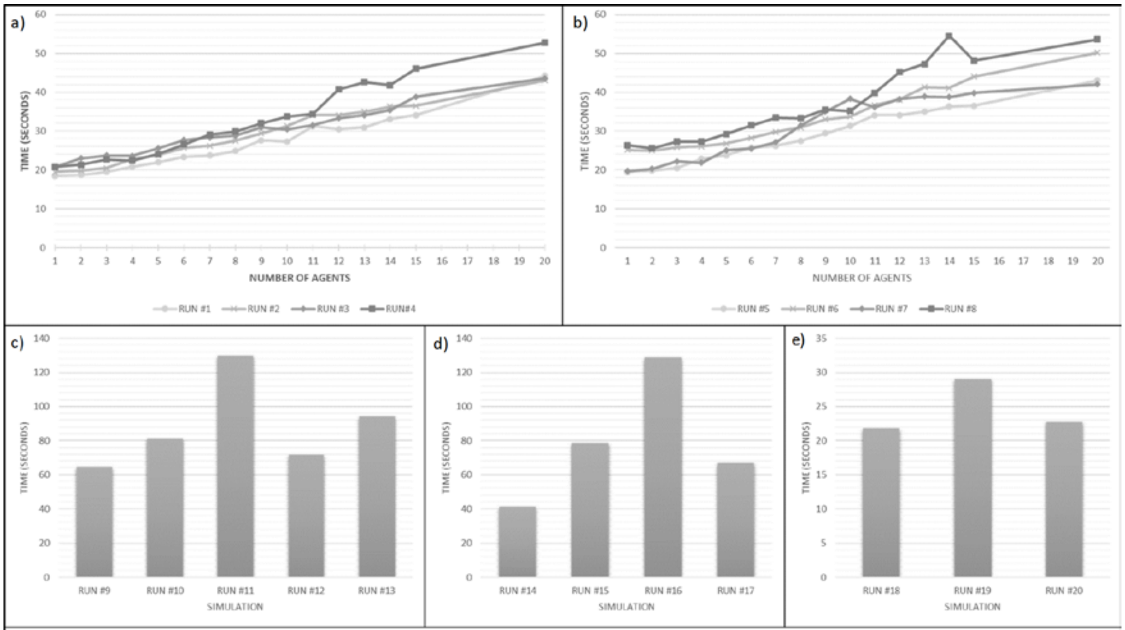
2.5.3. Unity simulations

The Unity simulations go beyond simple distance assessments and time calculations to explore the impact that the building, other evacuees, and obstructions have on the performance of the evacuation. These visualizations focus on evacuations from a conference room on the sixth floor to the nearest stairwell, from that same conference room to the nearest exit on the fourth floor, and from a sixth-floor office with the longest evacuation time in the 3D GIS analysis, to exits on the fourth floor. The simulation timer begins when the simulation starts, and stops when the evaluated agents have all crossed the target line at the defined destination. All the presented evacuation times represent the mean value from 10 individual simulations.

Conference room to stairwell

Our first set of analyses (Runs 1-4) in Unity estimate the amount of time required to move from the conference room to the nearest stairwell, and measures the impact of increasing the number of evacuees and/or adding physics enabled spring-loaded doors to the network (Figure 2.7). The addition of other agents and doors results in a 19.3% increase in estimated evacuation time. The results of this test set are presented in Figure 2.8.

Figure 2.7 Simulated Evacuations
(top) A screenshot of the evacuation simulation shows agents travelling from origin to destination. **(bottom)** Using the physics simulator within Unity it is possible to add moving obstructions to the simulation; in this case, spring loaded doors were added to the model to simulate the impact of the doors that exist in the real-world.



RUN	NUMBER OF AGENTS	AGENT SPEED	OTHER EVACUEES (#)	OBSTRUCTION (TYPE)	AGENT ORIGIN	AGENT DESTINATION
1	1-15, 20	STANDARD	NO	NO	6th FLOOR CONFERENCE ROOM	6th FLOOR STAIRWELL
2	1-15, 20	STANDARD	YES (28)	NO	6th FLOOR CONFERENCE ROOM	6th FLOOR STAIRWELL
3	1-15, 20	STANDARD	NO	YES (DOORS)	6th FLOOR CONFERENCE ROOM	6th FLOOR STAIRWELL
4	1-15, 20	STANDARD	YES (28)	YES (DOORS)	6th FLOOR CONFERENCE ROOM	6th FLOOR STAIRWELL

RUN	NUMBER OF AGENTS	AGENT SPEED	OTHER EVACUEES (#)	OBSTRUCTION (TYPE)	AGENT ORIGIN	AGENT DESTINATION
5	1-15, 20	STANDARD	YES (28)	NO	6th FLOOR CONFERENCE ROOM	6th FLOOR STAIRWELL
6	1-15, 20	VARIED	YES (28)	NO	6th FLOOR CONFERENCE ROOM	6th FLOOR STAIRWELL
7	1-15, 20	STANDARD	YES (28)	YES (GARBAGE BIN)	6th FLOOR CONFERENCE ROOM	6th FLOOR STAIRWELL
8	1-15, 20	VARIED	YES (28)	YES (GARBAGE BIN)	6th FLOOR CONFERENCE ROOM	6th FLOOR STAIRWELL

RUN	NUMBER OF AGENTS	AGENT SPEED	OTHER EVACUEES (#)	OBSTRUCTION (TYPE)	AGENT ORIGIN	AGENT DESTINATION
9	20	STANDARD	NO	NO	6th FLOOR CONFERENCE ROOM	4th FLOOR WEST
10	20	STANDARD	YES (53)	NO	6th FLOOR CONFERENCE ROOM	4th FLOOR WEST
11	20	STANDARD	YES (179)	NO	6th FLOOR CONFERENCE ROOM	4th FLOOR WEST
12	20	STANDARD	YES (53)	NO	6th FLOOR CONFERENCE ROOM	4th FLOOR TEST
13	20	STANDARD	YES (179)	NO	6th FLOOR CONFERENCE ROOM	4th FLOOR TEST

RUN	NUMBER OF AGENTS	AGENT SPEED	OTHER EVACUEES (#)	OBSTRUCTION (TYPE)	AGENT ORIGIN	AGENT DESTINATION
14	1	STANDARD	NO	NO	6th FLOOR OFFICE	4th FLOOR WEST
15	1	STANDARD	NO	NO	6th FLOOR OFFICE	4th FLOOR TEST
16	1	STANDARD	YES (199)	NO	6th FLOOR OFFICE	4th FLOOR WEST
17	1	STANDARD	YES (199)	NO	6th FLOOR OFFICE	4th FLOOR TEST

RUN	NUMBER OF AGENTS	AGENT SPEED	ROOM LAYOUT
18	20	STANDARD	EMPTY
19	20	STANDARD	REAL LIFE
20	20	STANDARD	MODIFIED

Figure 2.8 Unity Evacuation Simulation Results

a) Simple evacuation analyses conducted using GIS can fail to account for the complexity of the scenario. The time required for evacuees to reach the destination increases as the complexity increases, with the highest times recorded with doors and other agents as obstacles. **b)** Varying the speed of the evacuating agents within the simulations disrupts the flow of the evacuation and leads to increased evacuation times. Obstacles also disturb the flow; however, a critical mass is required before those obstacles changes the evacuation performance. **c)** As the number of agents within the VE increases, the time required for a given group to evacuate increases. Run #12 and #13 contain the same number of agents as run #10 and # 11 respectively, but provide another path out of the building, decreasing the time required for agents to evacuate. **d)** A simulated evacuation of an empty building does not properly test the performance of an evacuation route. When other evacuees are added to the scenario (run #16), the evacuation time increases. Building floorplans should be compared to real-world structures, as any discrepancies can result in inaccurate evacuation estimates. In this case, run #17 allows agents to evacuate the building earlier, through an exit that is present in building plans but not the building itself. **e)** The time required to evacuate a room varies per the conditions within that room. An empty room (run #18) does not represent real world conditions (run #19) or provide an accurate estimate of evacuation time. VEs such as these can be used to test modified layouts (run #20) with improved egress.

A second set of simulations (Runs 5-8) evaluate the impact that agent speed and obstacles may have on evacuation performance. In this case, the obstacle is a garbage and recycling bin with the same dimensions as those found on campus, and includes physics properties that allow it to move given sufficient external force (Figure 2.9). These tests have the same origin and destination as Runs 1-4 and test the same number of agents. The results are presented in Figure 2.8.

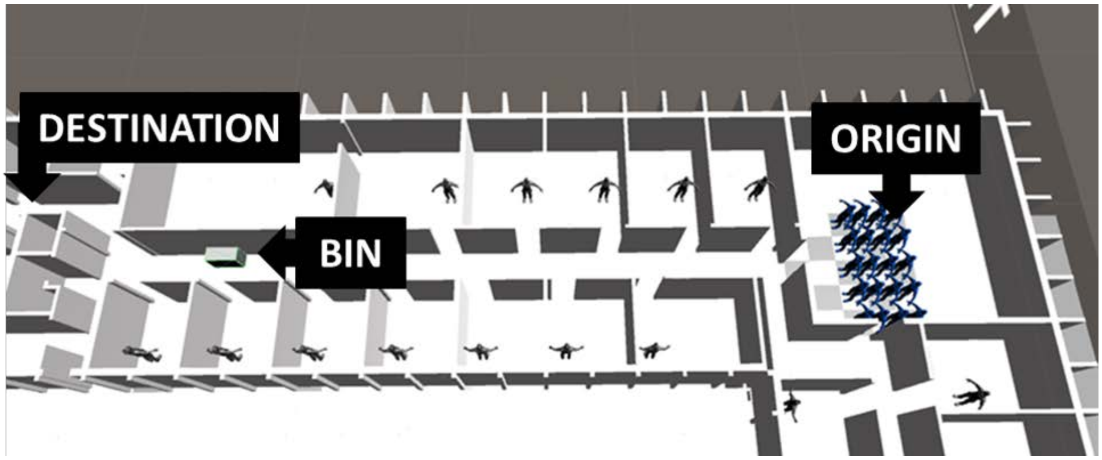


Figure 2.9 Simulated Obstacles
The simulation environment should attempt to replicate the conditions in the real world. Small obstructions can impact the performance of the evacuation. In this instance a garbage bin with physics properties was added to the Unity simulation.

Conference room to fourth-floor exit

This series of simulations (Runs 9-13) focuses on agents in the same conference room; however, these agents are programmed to evacuate to fourth floor exits with outdoor access. Each iteration was conducted 10 times to obtain an average value for the given parameters.

The other evacuees in these runs represent those people in offices and classrooms that are closest to the evaluated exits based on our 3D GIS analysis. Those runs with 53 other evacuees only account for people on the sixth floor, and those with 179 other evacuees account for people on both the fifth and sixth floors. The two different exits tested in these runs are the nearest exit that avoids the inside of the courtyard (west exit) and the test exit which adds an exit to the stairwell on the north side of the building that currently does not allow access to the outdoors without entering the potentially dangerous courtyard (Figure 2.10). Access to those doors resulted in an 11.5% and 27.4% decrease in time respectively, when compared to the prior two runs. The results of these tests are presented in Figure 2.8.

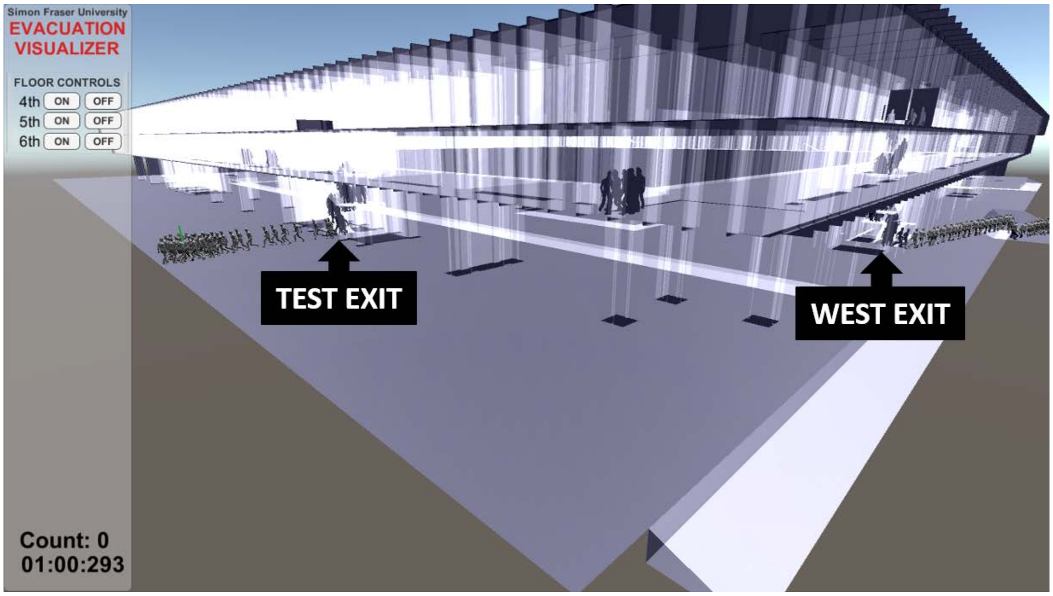


Figure 2.10 Testing Building Egress in Virtual Environments
A customizable VE allows the user to test 'what if scenarios.' In this case a test exit was added to a fourth-floor stairwell to measure the impact on the time required for a group of agents to evacuate the building.

Sixth floor office to fourth floor exits

This set of simulations (Runs 14-17) evaluates the ability of one evacuee to exit the building from an office on the sixth floor. That office is located nearest to the stairwells on the north side of the building that do not permit access to the outside of the buildings internal courtyard. The evacuee is programmed to evacuate the building through one of the exits used in Runs 9-13, assessing the impact of other evacuees and exit availability on evacuation performance. The results of these tests are presented in Figure 2.8.

Unity simulations with photogrammetry

The final set of Unity simulations (Runs 18-20) examines the impact that a buildings contents may have on evacuation performance. Three room layouts for the inside of the same sixth floor conference room used in other test runs were evaluated in these runs (Figure 2.11). The existing room layout was assembled into a 3D model from a series of photographs processed with PhotoScan photogrammetry software. The 3D model was uploaded into the Unity VE for analysis. These tests illustrate that the buildings contents, not just its structure, have an impact on evacuation performance. In the real-world, people are not lined up at the doorway, nor do they necessarily have a clear path to that doorway. With the 3D model of the interior, the evacuation time increased by 33%; yet with a modified layout, there was only an increase of 4.4%. The results of these runs are presented in Figure 2.8.

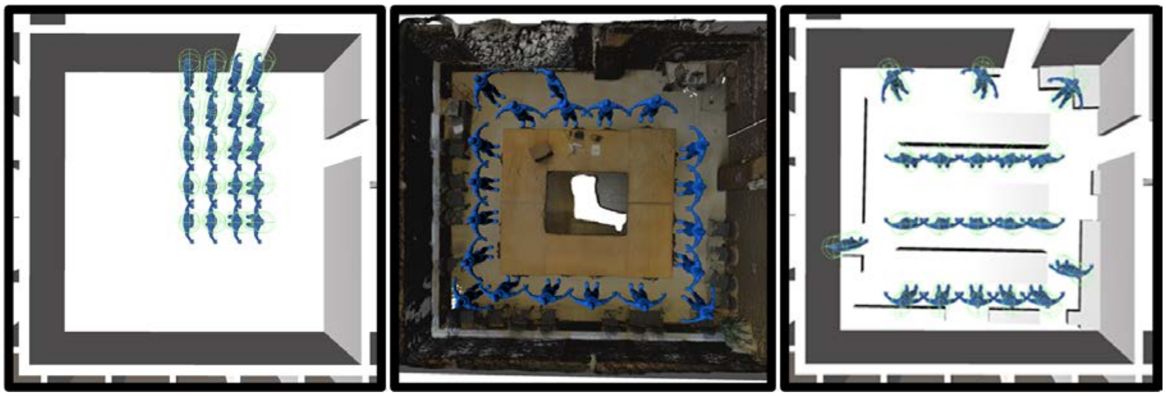


Figure 2.11 The Impact of Layout
(left) An empty room with evacuees waiting in line is not representative of the real world. **(middle)** Photogrammetry can be used to create 3D models of the real world, forcing agents to evacuate around the obstacles that exist in that space. **(left)** Crude representations of furniture can be added to the model and arranged to find the placement that optimizes evacuation performance.

2.6. Discussion

This paper explores our efforts to produce a set of workflows that highlight and address the challenges associated with modelling evacuations in complex institutional spaces. We have outlined the results from our 2D and 3D GIS analyses, and presented an alternative approach that fuses the spatial rigor of a GIS with the simulation capabilities of game development software. Furthermore, we have included photogrammetry as a tool for modelling real-world settings, and have shown that these models can be used within the simulation environment for evacuation performance impact assessments.

In the following sections, we will discuss the results from these analyses, and we will compare the limitations and affordances associated with each. We will evaluate each as an aid for emergency management professionals, commenting on their application to spatial analysis and data visualization.

2.6.1. GIS and emergency management

As we indicated earlier, GIS serves an important role in emergency management. The science and software is used to organize, analyze, and visualize spatial data in preparation and response to natural and manmade disasters. We have focused on the application of GIS to evacuation analysis, particularly for assessing evacuation routes and the time required to evacuate a building. Our analysis does not focus on agent based modelling, or more comprehensive GIS based network analyses with sophisticated algorithms for human behavior, but instead focuses on the dimensionality of the problem and the challenges associated with analyzing a 3D spatial phenomena.

Our examples of 2D and 3D network analyses highlight how GIS can be used to measure the distance from classrooms and offices to stairwells or exits. It can be used to assess the relative accessibility of those spaces using the existing network, or the implications of damage to that network, or to test the outcome of modifications to that network; all of which can provide useful information. However, Figure 2.12 exemplifies how, in our analysis, the removal of two doorways on the fourth floor affects distance (and time) measurements for those of the fifth and sixth floors, but only when evaluated using a 3D network. This suggests that dimensionality has serious implications on evacuation assessments, particularly for those floors without direct access to the outside.

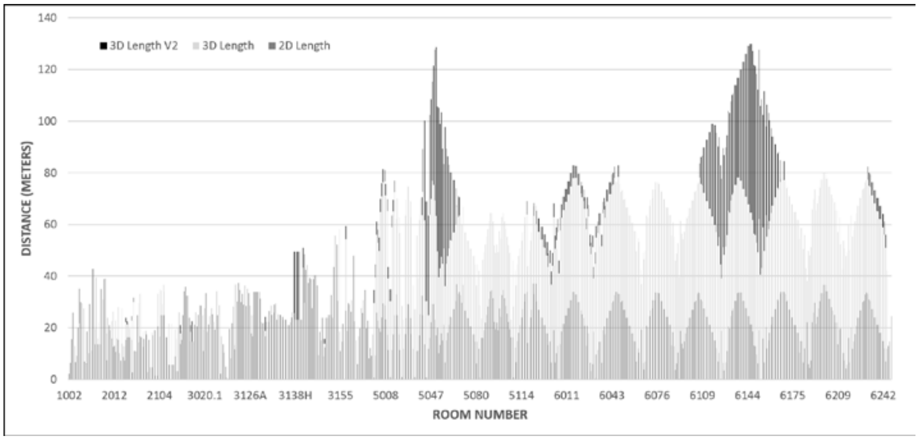


Figure 2.12 3D vs 2D Network Calculations
Adding a 3rd dimension to GIS based network analyses significantly impacts the distance to exit measurements. If those exits are potentially hazardous, they can be removed from the analysis. In this case, 3D length V2 blocks an exit which feeds into a courtyard; without it, some evacuees on the 5th and 6th floor must travel greater distances to exit the building.

The shift from 2D to 3D GIS analysis provides additional detail that is critical to the analysis. To properly assess the transportation network, you must accurately represent that network. However, that network contains more than just a third dimension, it includes other people, potential hazards, countless obstacles, and many features that are not captured by a network of nodes or splines. That network also fails to account for the space between the agent and the network, providing unrealistic access to that network. While GIS may be used for simple distance analysis as we have presented, inferences about time are risky, as it is difficult to account for the dynamic and complex nature of the situation.

Despite these limitations, GIS is unquestionably a useful tool for emergency management. One important function is the ability to present data for visual interpretation. However, GIS outputs in this instance are static representations of a dynamic phenomena; data goes into the GIS, spatial tools and techniques are applied, and data comes out. We can present that data many ways, but it is difficult, if not impossible, to produce a visualization of the process. For evacuation studies, that process provides valuable information.

2.6.2. Serious games and emergency management

The series of simulations that we have presented in this paper demonstrate the functional role that game development software can play in geospatial analyses. While this may not be their intended purpose, they serve an important role in what has be described as ‘not-quite-GIS,’ integrating the science of GIS with alternative methods of visualization (Elwood 2008). Beyond simply visualizing data in new ways, these technologies offer a workflow for incorporating the spatial and dynamic complexities that are problematic for GIS software.

Our research began with a set of validation tests to prove that Unity can be used for evacuation analyses. With flow rate validated, our goal was to then illustrate how changes to the environment can impact the performance of the evacuation. The addition of other evacuees, physics based doorways, and moveable garbage bins all had an impact on the time required for a set of evacuees to move from an origin to a destination. The point being, that sterilized representations of space are not representative of the real-world, and that GIS analysis, and many simulation software packages, fail to properly account for the complexities of the real-world. For instance, a GIS can represent the presence and impact of obstacles on network segments, but those obstacles are fixed in space – in reality, those obstacles can, and will, move during many events requiring an emergency evacuation. Similarly, many software packages enact prescribed scenarios, and are incapable of simulating the dynamic conditions of real environments, something game engines such as Unity excel with.

Our first set of analyses simulated the movement of evacuees from a conference room on the sixth floor to the nearest stairwell. In our 2D GIS analysis this stairwell represents the exit, as an actual exit could not be reached in 2D. In the GIS analysis, the total distance was measured at 33.80 m, and required between 16.10 and 22.53 sec of travel time depending on walking speed. It required an average of 18.73 sec to walk that route in the real-world. The results of our first eight simulations are presented in Figure 2.13. Our simulated results match the GIS estimate and the real-world time required to travel that distance, but only in situations where that conference room has two or less occupants, everyone travels at the same speed, the hallways are free from obstructions, and the doors are held open. There is therefore a much greater range in evacuation time than is presented by GIS analyses alone.

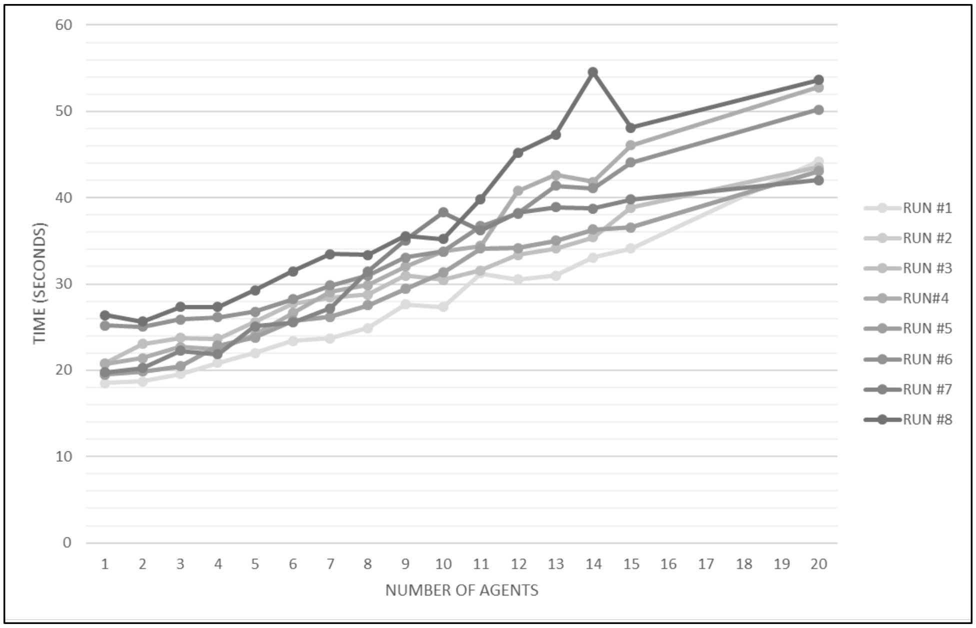


Figure 2.13 Variations in Evacuation Calculations
Determining the distance to an exit provides limited information about emergency egress. The results of these tests show that time varies depending on the conditions of the environment, and that in most cases 16.10 - 22.53 sec does not represent the time required to reach the destination.

In run #9 through #13 we again focused on the conference room and simulated different evacuation scenarios for a group of 20 agents. Run #14 through #17 focused on the evacuation of a sixth-floor office occupied by one evacuee. These sets of simulations tested the impact of an additional doorway to a stairwell on the fourth floor, and varied the number of evacuees in the simulation. The objective here was to highlight the ability to explore evacuation scenarios in the Unity VE. For those assessing evacuation flows, the VE provides a medium with which to test structural changes that may improve pedestrian dynamics.

The final three runs (#18 - #20) focus on the important choices that must be made when modelling complex spaces and the transportation networks associated with them. In a GIS, we use nodes and splines; in our case derived from shapefiles. In our Unity environment, as in many simulation software packages, we used architectural drawings to extract the 3D structure of the building. In both instances, we created a simplified version of the AQ, turning a complex building with even more complex internal features into a brutally simple structure. Although Unity allows the user to add complexity to the model with simple 3D shapes, these final simulations attempt to overcome that simplification using photogrammetry based 3D modelling.

In addition to modelling the collective evacuation of a room, it is possible to calculate the time required for individual evacuees within that room to escape from it. In these simulations (structured to match run #19) we again draw upon the photogrammetry based 3D model, and assign a number to each of the agents in the room. Each agent is then programmed to stop the timer when they have escaped from the room. The simulations were conducted three times for every agent position, providing an estimate of the required evacuation time from that point within the room. The evacuation times for each agent ranged from 2.92 to 26.61 sec, and are presented in Figure 2.14. This same methodology was applied to the modified layout and the results are presented in a VE based visualization (Figure 2.15).

The objective of this simulation environment was to provide emergency management personnel with a workflow that allows them to evaluate scenarios and test evacuation plans. They are virtual sandboxes for playing out what if scenarios. They overcome many of the limitations associated with GIS based analyses, including visualization. Unity allows developers to produce standalone programs for computers, mobile devices, and gaming systems, and supports virtual and augmented reality based applications. More on these topics will be covered in future manuscripts.

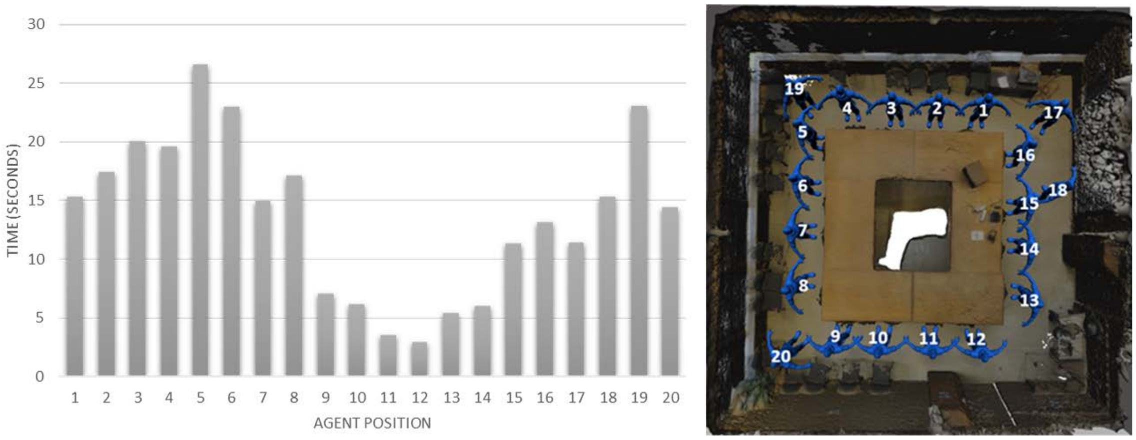


Figure 2.14 Room-scale Variations

The time required to evacuate a room varies depending on the number of people within that room. VE based simulations allow us to quantify the evacuation time based on agent position within that room. **(left)** A graph of evacuation time from numbered positions within a room. **(right)** The number corresponding to each agent position.

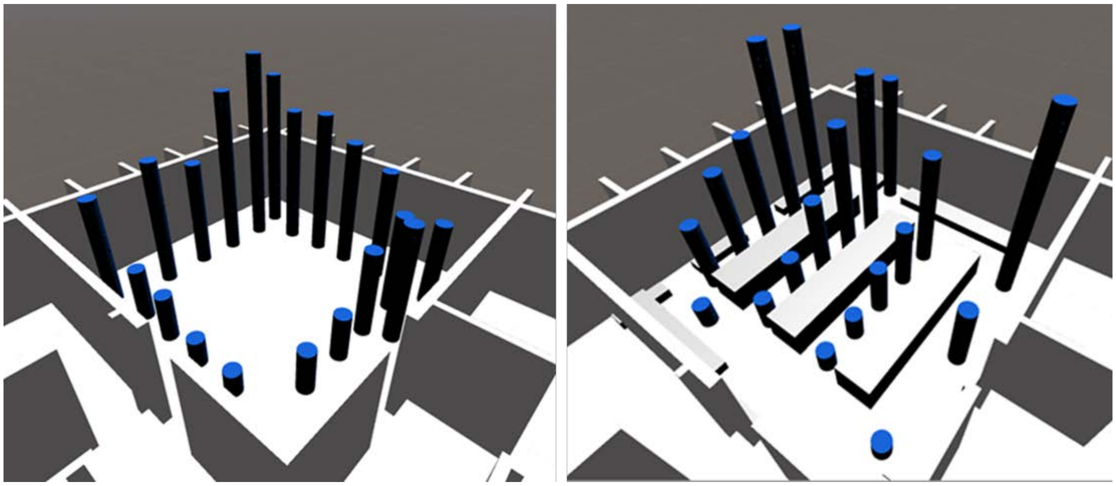


Figure 2.15 Room-scale Context

Furniture can impact evacuation performance. **(left)** A Visualization of evacuation times based on the current room configuration. **(right)** An altered floor plan and the impact on evacuation times.

2.6.3. Limitations

The workflow and visualizations presented in this paper serve as a method for uncovering the influential role that dimensionality and structural representation can have on evacuation analyses. They are not purported to be a solution to the problem, but rather, they highlight the variability and dynamic nature of the problem at hand and illustrate how the lens with which we view that problem influences the results. In the absence of real-world evacuation exercises, what data serves emergency personnel in their planning efforts?

Our GIS analyses utilize the network analyst function within the GIS software, which requires a shapefile representative of that transportation network. The network in our analyses represents all primary hallways within the AQ. However, a 10 m wide hallway and a 2 m wide hallway are both represented equally, yet they have very different carrying capacities. Furthermore, the distance measurements are indicative of the distance from the point on the network closest to the origin to the point on that network closest to the destination, and do not account for the distance required to get from within that origin to the network. Not to mention, having reached the destination on one is not the same as reaching it on the other, as you must account for the width of that hallway. These GIS analyses are therefore an estimate of distance, and should be used with caution; perhaps as informative pieces that focus more in-depth analyses.

The simulations that we conducted within our Unity VE are an example of how, as GIScientists, we can draw upon non-traditional software for geospatial applications. Unity was not designed to be an evacuation or crowd simulation software, yet it can serve a valuable purpose as such. The AI based agents, navigation networks, and visualization modalities are useful functions not found in GIS applications. The simulations that we have presented are an example of how that software's functionality can be used to inform decision makers, especially in situations where they might not understand the process or be able to visualise what it would look like. These VEs are not a replacement for real-world training, but are meant to supplement it.

2.6.4. Game based simulations for emergency management

The process of emergency management can be defined as an experiential process where we learn from our experiences as well as those of others. A great deal can be learned from others, but there is risk associated with applying that situation specific knowledge to alternative scenarios. Game based simulations provide what is essentially a laboratory for exploring those scenarios, as well as the research and theories of others, within the safety of a VE (Botelho et al. 2016).

At the core of emergency management is a drive to build resilience; to make sure that when faced with adversity we can overcome it. Preparedness, a stage of the emergency management cycle that could be described as its foundation, is focused on making sense of the unknown so that we are not overcome in times of crises. It is an attempt to make sense of what we could be faced with. That process of sensemaking is one that enables people to build new knowledge by interpreting information in context (Ntuen, Park, and Gwang-Myung 2010). Context, that unique set of circumstances that are the walls, halls, doorways, garbage cans, and people within a building, is critical to these spatial problems, and the workflow that we have presented provides inroads for that context. These VEs would allow emergency management organizations to visualize those circumstances, manipulate them, and learn from them.

2.7. Conclusions

The risks to people in institutional spaces, are highly influenced by the geometry and topology of physical space and infrastructure, the geometry and topology of human dynamics, and the geometry and topology of human behavior (and the execution of emergency plans) during evacuation events. In this paper, we have presented a workflow which merges the spatial science of GIS with the simulation capabilities of game development software, to capture the complex interactions between people and space during the evacuation of a building. As obvious as this may seem, careful considerations of the spatial granularity of representation are critical to the analysis and interpretation of how risky the architecture of institutional spaces may be.

We have situated our research in the fields of GIS, emergency management, game development, and visualization to highlight the multidisciplinary nature of the problem and the benefit of a non-traditional approach to solving it. Our Unity based VE demonstrates this non-traditional approach by combining the science of GIS with the creative freedom of game engines. In doing so we have provided a highly customizable sensemaking and visualization workflow that allows emergency management personnel to study evacuation performance. While this is not meant to replace real-world experience, it does provide possible relief from the financial and temporal burden associated with real-world exercises. Our objective was to allow planners to visualize that which they could previously only imagine.

Visualizing emergency scenarios is an important part of the process of understanding them. We have presented some basic visualizations using GIS and game engines, but there remains much to be accomplished. Game engines offer a richness of visualization potential, from immersive VEs that allow people to enter the scenario with head-mounted-displays, to mobile augmented reality interfaces that allow them to fuse the VE with the real-world. We hope that this research offers some insight into the future possibilities of emergency research, and motivates a collaborative effort to fuse disciplines and promote resilience.

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Chapter 3. Using situated augmented reality geovisualizations to contextualize 3D simulations of human movement in real space[2]

3.1. Abstract

Computer based evacuation simulations are an important tool for emergency managers. These simulations range in complexity and include 2D and 3D GIS based network analyses, elaborate agent based models, and highly sophisticated models built on documented human behaviour and particle dynamics. Despite the influence of the built environment in determining human movement, a disconnect often exists between the real-world and the way it is represented in these simulation environments. The proliferation of location aware mobile devices, along with a recent infatuation for augmented reality, has resulted in new wayfinding and hazard assessment tools that bridge that gap and allow users to visualize geospatial information superimposed on the real-world. In this paper, we report research and development to deliver new prototypes which explore the potential of mixed reality (particularly augmented reality) geovisual analytical systems – to study human movement in complex built environments, where multiple levels of architecture and thoroughfare infrastructure (corridors; paths; hallways; atriums) are embedded deep within buildings. We demonstrate how mixed reality visual analysis of intelligent human movement simulations built in virtual spaces, can become part of real space. This provides a fundamentally new way to view and link simulations of people with the real-world context of the built environment.

3.2. Introduction

Evacuation plans are an essential component of any establishment's emergency management efforts. The evacuation plan dictates the necessary set of actions to be observed by evacuees and emergency response personnel in the event of a disaster. Those actions are dependent on the characteristics of the hazardous event, as well as those of the population that is impacted by it. Therefore, there is not a general

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[2] A version of this chapter has been submitted to *International Journal of Digital Earth* under the co-authorship of Nick Hedley.

evacuation plan for all people and places; the evacuation plan must be developed in accordance with the identified risks and corresponding scenarios that could impact the affected population (Nunes et al. 2014). Context plays an extremely important role in the development of the evacuation plan, as the spatial and temporal characteristics of the disaster define the conditions and performance of the evacuation.

Evacuation plans are often developed with the support of simulation software, Geographic Information Systems (GIS), prescriptive governmental guidelines, and published experiences. The evacuation routes delineated by these plans often define the movement of people based on specific constraints (i.e. building codes and government policy) more than the non-linear dynamics of the evacuation as defined by the context under which it occurs (Cepolina 2005). An evacuation route is more complex than the path defined by the shortest distance from one place to another, and a failure to account for the dynamic interactions between people and the environment represents a flawed foundation from which to prescribe evacuation procedures. Emergency egress software developers have evolved their models to include these interactions; however, their spatial and temporal context represents a static characterisation of a dynamic environment that variably changes over time.

Recent work (in press) revealed the differences in simulation outcomes when using GIS, versus the artificial intelligence (AI) capabilities of 3D game-engines. That work revealed the limitations of GIS to represent the complexity of 3D institutional spaces and pathways of movement (changing widths; topology; erroneous floorplans; nonlinearity of human behaviours; effects of furniture; collisions; pileups; impedances of doors). In addition to the challenges of adequately modelling and simulating institutional space and human dynamics within them, the layout of the spaces themselves can often be multi-level, large-volume architectures that have evolved over time. This can result in corridor networks being buried deep within the architecture. GIS and architectural software have made some progress towards modelling the geometry of these often complex spaces (Thill et al. 2011, Eaglin et al. 2013, Zhou et al. 2015), though there are still many issues to overcome, to move beyond floor-by-floor planar representation and analysis and adequately represent and analyse institutional geometry and topology contiguously in three dimensions over time. The architectural community has arguably made more progress through building information modelling (BIM) which includes geometric and semantic building properties, inspiring BIM oriented indoor data models for indoor navigation assessments (Isikdag et al*.* 2013).

The purpose of this paper is to introduce the research and development that we have done to close the gap between virtual simulation spaces of analysis, and the real-world spaces where the outcomes of these analyses need to be understood. These interfaces represent an extension of our previous research (in press) that supports the application of game-engines (Unity) as a method for simulating evacuation behaviour. Harnessing the power of mobile technology and augmented reality (AR) based visualizations, we have developed a workflow that brings game-engine based AI into the real-world for situated visual analysis of simulated human movement in real environments. The objective is to contextualize AI-based 3D spatial evacuation simulations by superimposing virtual evacuees on the real-world so that emergency managers can visualize simulated human movement, fully situated in real space, and identify the possible impedances to emergency egress that are missed, or inadequately represented, using current methodologies.

3.3. Research context

The research presented in this paper is an extension of our ongoing efforts to illustrate the importance of representative virtual spaces for evacuation simulation and egress analysis which capture the complex and dynamic nature of real-world built environments. Simulation environments, like maps, may contain implicit biases as a result of who created them, for what purpose, with what level of expertise or experience, and using which methods. Prioritisation of feature importance, or the standards that are established to ensure the quality of their representation of reality, are choices made by analysts directly, or may reflect limited technical and data asset options. These choices are not necessarily underhanded attempts to hide the truth, but reflect the requirements of the software and the prescriptive nature of building codes and regulatory guidelines. However, simply quantifying how long it takes to get from one point to another is an extremely linear approach to what is a very non-linear problem. Evolving emergency scenarios, human decision-making, and unexpected circumstances in three-dimensional built environments are not well served by many conventional spatial analytical methods.

Assessing human crowd evacuation or tsunami inundation, simply by quantifying shortest-path distances, characterizing positions of final crowd destinations, or computing the line of maximum inundation – only provides us with a limited analytical narrative. Revealing the dynamic properties of the space and the agents throughout the event may be more informative than the final geometry alone. An assumption that the geometric properties of the landscape are constant is risky, and relying on simulations based on static database representations makes analyses that include everyday circumstances impossible, such as: temporary objects (such as stages and furniture); doors being locked or out of order; movable objects being knocked over to create dynamic impedances. Virtual geographic environments (VGEs), which allow for computer-aided geographic experiments (CAGEs) and analyses of dynamic human and physical phenomena (Lin et al. 2013), are ideal for the simulation and visualization of human movement in built spaces. The visualization capabilities of GIS and simulation software have evolved to allow the user to see the process and not just the result, yet that process continues to be constrained by the software and the resolution of the model. In the following sections, we will evaluate some of the current tools used by emergency managers for evacuation assessments.

The other significant emerging opportunity, is to use the power of situated visual analysis to take simulations developed in virtual spaces, and link them to the real spaces they aim to characterize. Elsayed et al. (2016) combined visual analytics with AR for what they termed situated analytics, enabling analytical reasoning with virtual data in real spaces. In subsequent sections, we discuss the potential of situated mixed reality geovisual analytics in emergency management.

3.3.1. Emergency management

Emergency management is a multifaceted framework that is designed to help minimize the impact of natural and manmade disasters. It is a cyclical process consisting of four components: mitigation and prevention, preparedness, response, and recovery (Emergency Management British Columbia 2011, Public Safety Canada 2011). GIS based analyses and evacuation models provide valuable contributions to all components of the cycle (Cova 1999).

A GIS is an important tool in the field of emergency management. These systems, and the science behind them, have been used to monitor and predict hazardous events, to form the foundation of incident command systems, to coordinate response efforts, and to communicate critical safety information to the public (Cutter 2003). Furthermore, GIS based spatial analyses can be applied to evacuation assessments at all scales, from large scale evacuations of entire cities, to small scale evacuations of multilevel buildings or the individual floors within them (Tang and Ren 2012). The complex transportation networks (i.e. roads or hallways) in these analyses are represented by an interconnected system of nodes, the defining details of which are contained within their associated attribute tables. Maintaining those attribute tables, as well as the algorithms which bring the model to life, are major challenges for GIS based analyses (Wilson and Cales 2008). The changes in the real-world must constantly be documented in the GIS for future analyses to be accurate.

Accurate estimates of the time required to evacuate a building are critical in the design of new infrastructure that must meet specific code requirements. These performance-based analyses range from hand written equations to complex computer based models, all of which are focused on assessing the safety of the building (Kuligowski et al. 2010). This assessment can be used to compare the safety of different architectural designs prior to construction, or to compare different egress strategies on pre-existing structures (Ronchi and Nilsson 2013). Regardless of the application, the defining element of these egress models is the accurate representation of human behaviour, and not the specific details of the building (beyond the structure itself). Each model presents a simplified version of human behaviour that is based on the model developers level of knowledge, and relies on their judgement as to what aspects of that behaviour are important (Gwynne et al. 2016). Furthermore, these models often require that users input a significant amount of behavioural data themselves, and that they construct the building manually or extract the structure from CAD drawings (Gwynne et al. 2016). Evacuation modelling is therefore highly subjective, relying on the discretion of the developer as well as the user.

Videogame development software has emerged as a flexible platform from which to conduct evacuation modelling. While software such as Unity was not designed for evacuation analyses, researchers have proven the results from Unity based simulations match what is published in the research literature (Ribeiro et al. 2012, Chiu and Shiau

2016). These game-based environments are capable of simulating human movement using built-in physics engines, navigation meshes, and AI based agents. They are compatible with a wide range of 2D and 3D formats, including many of the outputs from a GIS, and can be used to create a wide range of visualizations. However, the ability to produce experiential virtual environments (VE) that can be used to train evacuees and responders, as well as to plan emergency responses and evaluate their efficacy, provides an added level of value absent from GIS analyses and egress modelling. Researchers have developed game-based VEs that teach children the importance of fire safety and allow them to experience an immersive, head mounted display (HMD) based simulation of an evacuation from a structural fire (Smith and Ericson 2009), and have used surround displays and HMD based environments to test way-finding procedures and to evaluate the effectiveness of emergency signage (Tang et al. 2009, Meng and Zhang 2014). Advancements made with game-based environments are beginning to close the gap between the simulation space and the real-world.

The formation of an evacuation plan is a scientific process that involves the assessment of risk and the careful consideration of potential life threatening scenarios. Like maps, computer simulation spaces offer subjective representations of the real-world. The aforementioned tools that are employed to help formulate the emergency plans for those spaces are attempting to replicate the constantly changing physical and human environments, which fluctuate not only over space and time, but with the lens through which they are viewed (Torrens 2015). While game engines themselves cannot overcome the issues of subjective spatial representation, they provide an opportunity for additional human-computer (immersive) interaction and physics enabled simulation environments, reducing the prescriptive nature typical of current egress models. Game engines also provide a platform for the development of new tools that change the way we visualize the phenomena, effectively enabling situated analysis of simulated human movement in real space.

3.3.2. Geovisualization

Geovisualization is a multifaceted field involving the visual exploration, analysis, synthesis, and presentation of geospatial data (Slocum et al. 2001, Kraak and MacEachren 2005). Geovisualization combines the methodologies from cartography and GIScience with the technologies developed for GIS, image processing, computer graphics (including game development, animation, and simulation) (Bass and Blanchard 2011), and mixed reality (Lonergan and Hedley 2015). The objective is to provide new ways to visualize geospatial problems, thereby revealing the complex structures of, and relationships between, geographic phenomena (MacEachren and Kraak 2001). As they relate to emergencies and hazards, geovisualizations have the potential to influence risk perception and the communication of risk, and could improve disaster mitigation, preparedness, response, and recovery (Bass and Blanchard 2011).

Geovisualizations can be applied to emergency preparedness using an array of interface technologies. Each of these interfaces is situated somewhere along the "Reality-Virtuality Continuum" that was introduced by Milgram et al. (1994) to help classify the relationships between an emerging collection of visual display systems (Figure 3.1). At one end of the continuum there are real environments (RE); any environment containing exclusively real-world objects that are viewed either in person, or using some form of video display (Milgram et al. 1994). At the other end of the continuum there are VEs; any environment that consists solely of virtual objects that are viewed using a video or immersive display system (Milgram et al. 1994). Between these two extremes lies mixed reality (MR); any environment containing a combination of real and virtual content. The MR environment can be further subdivided according to the proportion of real and virtual content. AR environments are primarily real spaces supplemented with virtual content, and augmented virtuality (AV) environments are primarily virtual with added real-world content (Lonergan and Hedley 2014).

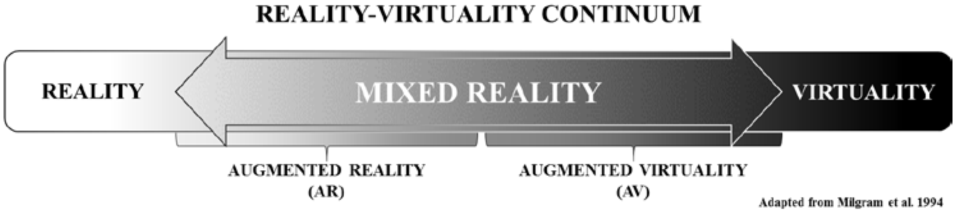

Figure 3.1 Reality-Virtuality Continuum
A modified representation of the reality-virtuality continuum introduced by Milgram et al. (1994).

The application of these technological interfaces to emergency management has the potential to transform the way in which we prepare for emergencies; not for their novelty, but for what they allow the user to visualize, how they allow them visualize it, and how they help the user comprehend the spatial phenomena at hand. New knowledge formation and sensemaking activities are supported by interactions with visualization tools (Pike et al. 2009, Ntuen et al. 2010), and a combination of visualizations provides greater opportunity for data exploration and comprehension (Koua et al. 2006). By applying multiple methods of visualization to emergency management the user is better equipped to appreciate the phenomena, perhaps shedding light on that which may be overlooked or exposing that which cannot be seen.

3.3.3. Situated geovisualizations

Geovisualizations are designed to improve one's understanding of geospatial phenomena by creating a cognitive connection between abstract information and the real-world. Metaphors are often used to facilitate that connection, as they help create a meaningful experience that users can connect to their experiences in real-world spaces (Slocum et al. 2001). However, emerging 'natural' interfaces – such as tangible and mobile augmented reality – are demonstrating that interface metaphors are less necessary with certain AR applications, as these AR interfaces create a direct connection between geospatial information and the real-world through strong proprioceptive cues and kinaesthetic feedback (Woolard et al. 2003, Shelton and Hedley 2004, Lonergan and Hedley 2014).

AR interfaces can be generally categorized as either *image-based* or *location-based* systems (Cheng and Tsai 2013). Image-based AR (also known as *tangible AR* or *marker-based AR*) uses computer vision software to recognize the image and then renders virtual objects on the display system according to the position and alignment of that image in space. Location-based AR (or *mobile AR*) uses GPS or Wi-Fi enabled locational awareness to pinpoint the location of the user, and superimposes virtual information on the display system according to its position in space. Location-based AR facilitates the cognitive connection between the real-world and virtual information without the metaphor, allowing the user to reify abstract phenomena in real-world space and in real time (Hedley 2008).

This *real-time reification* (RTR) of geospatial information aids in the process of spatial knowledge transfer by allowing the user to connect the virtual information on the display to the real-world, in situ (Hedley 2008, 2017). The situated nature of location-based AR generates a tacit learning environment, where users draw on cognitive strategies to make sense out of complex, and often abstract, phenomena (Dunleavy et al. 2009). Location-based AR holds the ability to provide spatial context, which when missing, often hinders our capacity to connect abstract information to real-world phenomena.

3.3.4. Applied MR

Novel applications

Modern applications of AR and VR have received plenty of attention recently. Perhaps the most widely recognized example of mainstream AR is Pokémon Go, a location-based AR application for mobile devices that superimposes Pokémon characters on the landscape and tasks players with their capture. This is just one of a number of recent applications of AR and VR to gain notoriety; however, the concepts behind these technologies are not new - VR was first introduced in the 1960s and AR in the 1990s (Cheng and Tsai 2013). The recent media attention towards and public adoption of these technologies is primarily the result of obtainability, as powerful mobile technologies and a collection of HMDs have become more affordable. With mainstream acceptance will come a greater number of AR applications for education, business, healthcare, entertainment, and much more.

Geographic applications

Geographic applications are particularly well suited for MR interfaces, as the scale, complexity, and dynamic nature of many phenomena makes them difficult to study in situ, and translating concepts from print to the real-world can be cognitively demanding. AR has been used to augment paper maps with additional information (Paelke and Sester 2010), to view and interact with 3D topographic models (Hedley et al. 2002), to assist with indoor and outdoor navigation (Dünser et al. 2012, Torres-Sospedra et al. 2015), to reveal underground infrastructure (Schall et al. 2009), and even to simulate and watch virtual rain (Lonergan and Hedley 2014) or virtual tsunamis (Lonergan and Hedley 2015) interact with real-world landscapes.

Emergency management applications

The number of AR interfaces that have been designed specifically for emergency management activities is limited. Some aid post-disaster building damage assessment (Kim et al. 2016), while others help with navigation and hazard avoidance (Tsai et al. 2012, Tsai and Yau 2013). Hazards may not always be visible or apparent, and AR can help to raise awareness and reduce risk through situated visualization. Chan et al. (2012) demonstrated the potential of AR to superimpose illuminated risk-encoded evacuation routes and egress markers on real landscapes. Their work reveals normally invisible risk, quantifies it, and provides citizens with an opportunity to see their everyday surroundings from a risk assessment perspective.

3.3.5. Situated AR for emergency management

AR interfaces provide a medium for users to enhance real-world environments with virtual information. In many respects emergency management deals with hypothetical situations that could benefit from AR interfaces (i.e. what an evacuation would look like). In the preceding sections of this paper, we outlined some of the resources used in emergency management to analyse emergency egress and highlighted some of the problems associated the representation of real-world environments in digital spaces. In the following sections, we present the work we have done to develop situated AR interfaces that enable visual analysis of human movement in real-world spaces. Our objective is to provide a workflow that supplements current toolsets and allows evacuation planners to compare dynamic AI-based evacuation movement against real-world features in situ, thus overcoming the problems of subjective spatial representation.

3.4. Methodology

We present here the work behind a set of new AR interface prototypes for the simulation and visual analysis of human movement, set in the context of real-world environments. We build upon our previous work which highlights the impact that scale of representation has on evacuation simulation outcomes, and the problems associated with modelling dynamic environments (in press). In the following sections, we describe the hardware and software used in the development of these interfaces.

3.4.1. Interface design

The visualizations presented in this paper were developed for mobile devices using the Android operating system. The chosen operating system is a reflection of the available technology and the developer permissions associated with it; this workflow could easily be adapted for Apple or Windows based devices. Our prototypes were tested on two Samsung Galaxy smartphones (S4 and S7) and a Samsung Galaxy tablet (Tab S). These mobile devices are compact, yet powerful enough to run the simulations efficiently, and have the built-in cameras required for image recognition. Location based services are also available on these devices and could be used for location-based AR; however, the accuracy of these systems was determined to be insufficient for our analyses. Any error in alignment caused by inaccurate or unstable positional data would translate to misalignment of the AR based geovisualization.

3.4.2. AR tracking

The prototypes that we have developed are an example of image-based AR. The software has been trained to recognize (track) an image, and uses that image to render and align the virtual content according to the position and size of that image relative to the position of the user (camera) in the real-world. One of the most common types of images used for AR is a coded black-and-white image similar to a QR code (Cheng and Tsai 2013). The high contrast of these images is ideal for image recognition by the software. These prototypes use what is known as *natural feature tracking*, where the software can be trained to recognize any visual feature. The performance of the augmentation is dependent on the contrast within the image, thus natural features must be chosen carefully to ensure optimal performance. In these examples the software has either been trained to recognize the shape of a building (from a photograph) or a specific fiducial marker.

3.4.3. Development

The workflow used to produce these prototypes is just one example of several methods for producing AR based geovisualizations. Regardless of the workflow, there are some essential components, including 3D objects, specialized software, and a display device. In the following subsections, we outline the development of our prototypes.

3D modelling

The foundation of our prototype is a 3D model of the building in which our simulation will take place (Figure 3.2). Each of the 3D models were constructed using SketchUp 3D modelling software. An architectural drawing (.dwg file) of the floorplan for each floor within the building was imported into the software, and the 3D structure of each was then extruded from the 2D drawing per building specifications. The floors were then aligned one on top of the other, ramps were added to represent the stairwells connecting each floor, and the completed models were exported as 3D files (.fbx or .obj).

Figure 3.2 Digital Models of Multilevel Buildings
(top) A real-world view of one of the buildings used in the evacuation analysis (author photo).
(bottom) A 3D re-creation of that building as seen in the VE.

3D virtual environment

A software system that was capable of AR integration, supported Android development, and contained 3D navigation networks, artificial intelligence (AI) based agents, and 3D physics was required for these prototypes. The software that we used to accomplish this was the Unity game engine (version 5.3.4) with the Vuforia AR software development kit (SDK).

Unity contains a built-in feature known as a navigation mesh, that defines the walkable area within the VE (Figure 3.3). A navigation mesh was created for each of the 3D models, the specifications of which are defined by the dimensions of the people (AI agents) within the VE. These prefabricated AI-based agents are used to simulate the movement of people within the VE. The characteristics of those agents are defined by average adult male height and shoulder width, and their walking speed is fixed, based on prior evacuation analyses (in press), and falls within a range of documented evacuation walking speeds (Rinne et al*.* 2010).

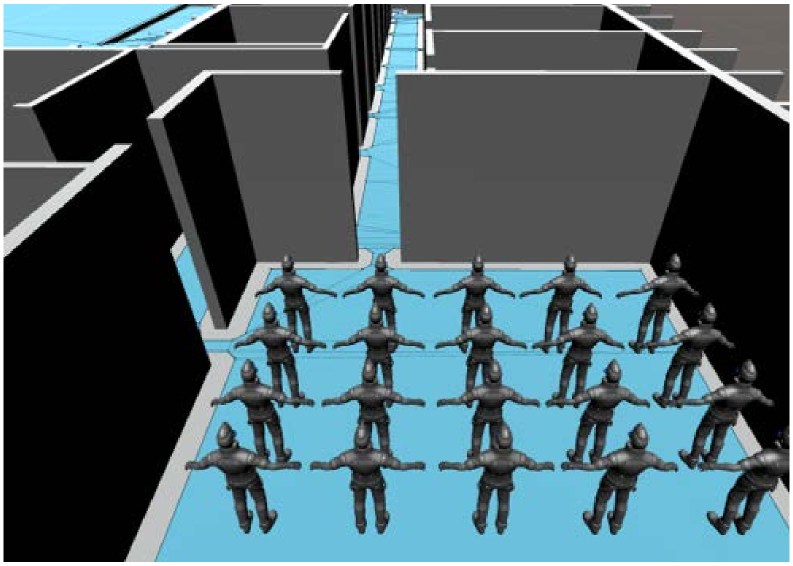

Figure 3.3 Unity's Navigation Mesh
The movement of the AI agents in the simulation is restricted to the navigation mesh (the blue regions on the floor).

Vuforia is a popular piece of AR software that integrates seamlessly with Unity. The SDK and the accompanying developer portal allow the user to create customized AR applications as well as image targets for natural feature tracking. Our VE was developed around those specialized targets, and any 3D objects attached to the targets are rendered in AR when the image is being tracked by the mobile device's camera.

Android deployment

Unity supports development for a wide range of platforms including mobile devices, computers, and videogame systems. The Android build support used in this research was installed as part of the Unity software package. Additionally, the Android SDK and Java development kit (JDK) were required. Once installed and properly integrated with Unity, the application can be deployed directly to a mobile device via USB connection.

3.5. Situated AR simulations

Our research focused on the production of a workflow and a series of prototypes that could be used for evacuation analyses situated in real environments. The prototypes presented in the following sections demonstrate these assessments at different scales, and assess movement from the interior and exterior of a building. The first two examples demonstrate image-based AR developed around images of a building, and the second two using a portable image target that can be positioned for analyses in different locations.

3.5.1. AR example #1

The first AR based geovisualization simulates the movement of evacuees as they move from various locations inside a multilevel building to a single destination outside of that building. The simulation contains a 3D digital elevation model (DEM), a 3D model of the building, and AI agents. The DEM and building renderers have been turned off so that only the agents and their pathways are augmented onto the landscape. Our objectives were to enable the user to analyse the movement of people as they evacuate the building, and to provide an interface that allows for the comparison of agent movement to the physical features of the built environment. This provides an opportunity for situated visual analysis related to queries such as: how many evacuees would be impacted by the bench and statue in front of the main door? These analyses could then be used to guide more complex computer based evacuation simulations that test the impact of those features on emergency egress.

In this example, a photograph of the building was captured with the same Samsung tablet that runs the application. That photograph was converted into an image target using Vuforia's online developer tools, and was then uploaded to the Unity VE. That image target was positioned in the scene so that the features of the building in the image align with the features of the building in the model. When the user positions themselves in front of the building and directs the devices camera towards the building the software searches for the features that are present in the image and displays the evacuees on the screen as augmented 3D content on the landscape (Figure 3.4).

Figure 3.4 AR Example 1
(main) The AR application recognizes the features of the building and supplements the real-world with dynamic, virtual evacuees, providing an opportunity for situated evacuation analysis. **(inset)** A view of the tablet being used for situated AR analysis.

This visualization was inspired by a conversation with an emergency management team, in which they stated that they do not know what it would look like if everyone was forced to evacuate. Our prototype demonstrates that AR could be used to visualize the mass evacuation of people from a building. This could provide emergency management officials with the experiential knowledge that is gained through a real evacuation event, or a full-scale evacuation exercise, without the associated temporal and financial overhead.

3.5.2. AR example #2

Our second AR prototype was developed using the same principles as the first, but focuses on a specific section of that same building. Instead of assessing a mass evacuation, it addresses egress through one of the main entrances. A photograph of that entrance was used to create an AR image for natural feature tracking, therefore when the mobile device's camera is directed towards the doorway, the display reveals virtual content superimposed on the real-world (Figure 3.5).

Figure 3.5 AR Example 2
(left) The AR software has been trained to recognize the features of the building from a photograph. **(middle)** When the device's camera is aimed at the building the application searches for the features in that photograph. **(right)** Once the software has recognized the image it superimposes the virtual evacuees on the real-world.

The complex nature of the built environment can sometimes result in structural features in peculiar places. This example highlights one such case, where a support column for an overhead walkway is positioned at the bottom of the staircase that leads to the main entrance. The column (and a garbage can) are positioned such that they could impact egress from the building. This AR interface allows the user to visually assess their potential impact based on the simulated movement of the building's occupants that would be expected to evacuate through that doorway.

3.5.3. AR example #3

Our third example of situated AR focuses on the movement of people within a building. The built environment is dynamic, changing as people and objects move over time. Yet it is often represented as a static set of features, or simply as an empty 3D structure. Our situated AR based egress analyses overcome these obstacles by placing the analysis in the real-world spaces being evaluated.

This prototype was developed using image-based AR, and requires a specific printed image target. The position and size of that target in the real-world must match the position and size of that target in the VE so that the AR simulation aligns properly with the building. In this example the VE includes a 3D model of the building and several AI agents. The 3D model of the building is not rendered in the AR application, but is used to provide the necessary occlusion that prevents the user from seeing agents through walls. When the user places the image target at the designated position and directs their mobile device at it, virtual agents are displayed traveling from their offices to the nearest stairwell (Figure 3.6).

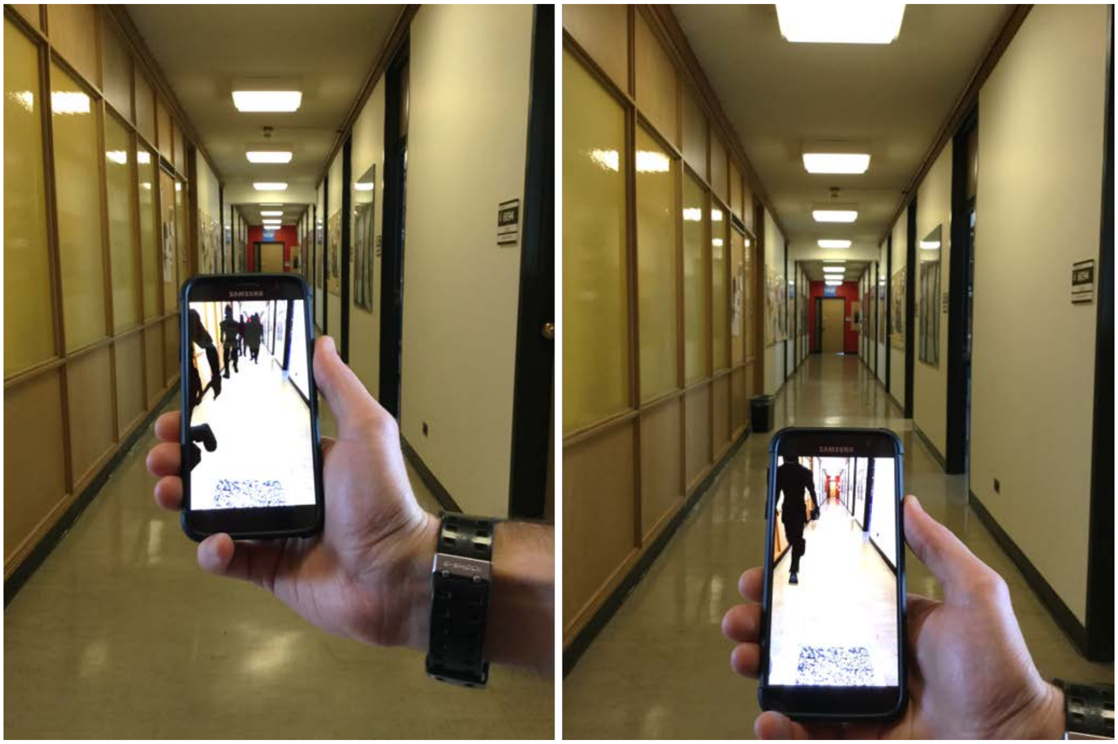

Figure 3.6 AR Example 3
AR allows for situated analysis of virtual human movement in real space. These images depict the application in use, displaying simulated movement of evacuees through one of the 6th floor corridors.

The objective of an AR interface like this one is to identify the features within the built environment that could impede egress, but which are not typically accounted for in computer based egress analyses (or were not present when that egress model was constructed). Situated analyses could determine that those features would have little impact on egress, or could be used to identify features that must be included in the egress model for more in depth analyses of their impact. Doors are an example of dynamic features that are not accounted for in models, but which have an impact on human movement in real life. While algorithms attempt to account for the impacts of doors, the characteristics of the doors themselves are not constant over space and time. Furthermore, one doorway may only serve a small population, while another may be used by hundreds of evacuees; therefore, any assumptions about impedance are not universal to every doorway. AR interfaces such as this could be used to assess the movement of people through these features (Figure 3.7).

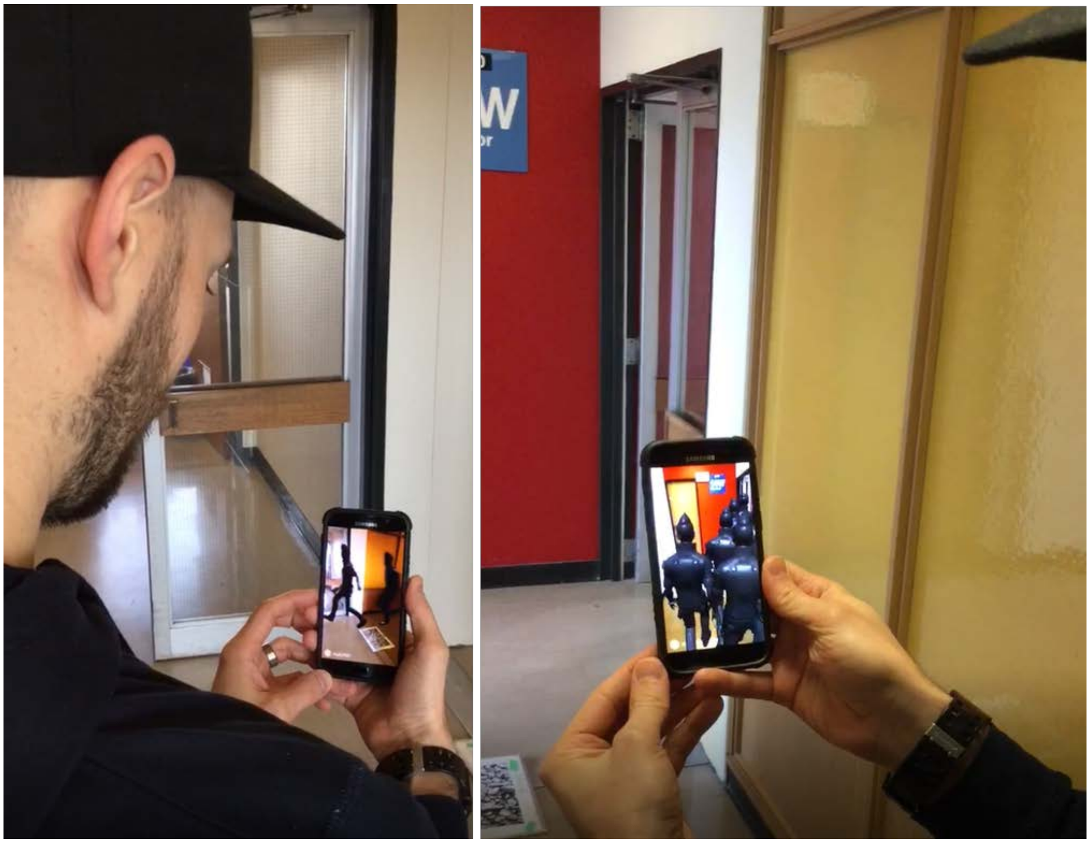

Figure 3.7 Situated Impact Analysis
Situated AR analyses can be used to address egress around specific building features (i.e. doorways, benches, garbage cans). In this case an assessment of the number of people that would travel through a doorway during an evacuation.

3.5.4. AR example #4

Architectural drawings are the foundation for building construction in most egress modelling programs, and therefore in any evacuation assessment based on them. Of the 26 egress models evaluated by Kuligowski et al*.* (2010), 21 were compatible with CAD drawings which are touted for their efficiency and accuracy. Identifying errors in these models is difficult, as the builder (or viewer) must be familiar with the structure and (or) cross-reference the features in the drawings with those in the real-world. That task is nearly impossible if the modelling and simulation are conducted from a remote location. Our final example of situated AR egress analysis illustrates how AR could be used to confirm the accuracy of these models.

This example uses the same model, agents, and image target as example 3. The image is placed outside of the building to assess the movement of people from their offices on 6th floor to the exterior of the building on the 4th floor (Figure 3.8). The 3D model of the building was developed from architectural drawings supplied by the institution and posted on their website, so it is assumed that these are accurate representations of the building's features.

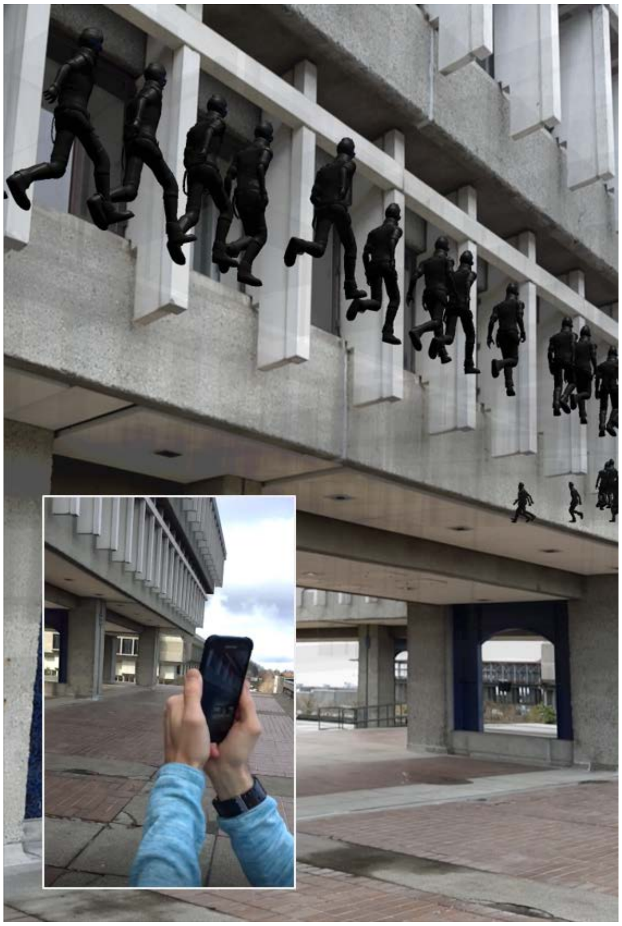

Figure 3.8 AR Example 4
AR image targets can be positioned anywhere, as long as their position in the real-world matches their location in the virtual environment. In this instance, the image position on the outside of the building allows for the visual analysis of human movement within it. **(main)** A screenshot of virtual evacuees superimposed on the real-world. **(inset)** The author using the AR application.

The results of this situated simulation reveal that agents can exit the building through a doorway on the north side of that stairwell that is not present in the real-world (Figure 3.9). While an exit is present on the south side of that stairwell, it leads to an interior courtyard which could be a hazardous environment after an event such as an earthquake or fire. Therefore, any egress analysis based on that incorrect architectural drawing would be inaccurate and could potentially place people in danger if they are taught to evacuate based on those inaccurate assessments. AR provides the context that is required to identify modelling errors by connecting the simulation space with the real-world.

Figure 3.9 Situated Egress Analysis
Situated AR can be used to ensure the accuracy of the 3D models used in evacuation analyses. In this instance the location of a doorway in the architectural drawings does not match the real-world layout of the building; therefor, agents can evacuate through a doorway that does not exist. **(left)** The author assessing human movement using situated AR. **(right)** A screenshot of the virtual agents evacuating through a non-existent doorway.

3.6. Discussion

The work that we have presented in this paper serves as an example of how AR can be used to bridge the gap between simulated evacuation analyses and the real-world. Our workflow helps to overcome the limitations associated with GIS based analysis and egress modelling, but is not a replacement for them. AR based analyses are a tool to be used by emergency management personnel for situated evacuation analyses, supplementing and informing the existing workflow in an attempt to improve overall emergency preparedness.

In the following section, we discuss some of the limitations observed during the development and testing of these prototypes, and suggest possible areas for future research and development related to situated AR based movement analyses. We also comment on the application of this technology to current emergency management practices.

3.6.1. Limitations

AR applications could be a valuable and powerful tool for the visual analysis and communication of emergency egress in the built environment, but it is critical that the virtual-world and the real-world are seamlessly aligned, and that their connection is sustained throughout the experience. Accurate tracking of the image and registration of objects to that image are fundamental to any successful AR application. Instead of focusing on issues of tracking and possible solutions to that problem, we focus here on specific limitations associated with occlusion and depth perception.

Issues of occlusion arise when virtual objects that should be hidden behind real-world objects are superimposed in front of them. For example, if the situated AR simulation is analysing the movement of virtual people down a hallway, any virtual people that are not in that hallway (i.e. are still in an office) should not be visible. If they are visible, it becomes extremely difficult to discern which ones are, and are not, in that hallway. Overcoming occlusion is a major issue for AR, and the solution often lies in the development of controlled environments based on prior knowledge of the real-world (Lonergan and Hedley 2014). In this case, an invisible 3D model of the building was placed in the VE to match the real-world structure so that any virtual objects behind the invisible walls are not rendered on the AR display. However, what we could not overcome were occlusion issues related to objects not contained within our VE (i.e. garbage cans, benches, and doors). Potential solutions to these occlusion issues lie in technologies such as Google’s Tango, where the AR experience does not rely on images or positional information, but uses computer vision for real-time contextual awareness (Jafri 2016).

In the case of our AR examples that are situated outside of the building, occlusion is not an issue since the objective of the visualization is to reveal the evacuation pathways within that building. Yet in doing so, we encountered depth perception issues, where it becomes difficult to tell which agent is on which floor, or which agent is on which side of the building. To overcome this problem, agents and their pathways could be colour-coded by floor, or additional functionality could be added to the application that would allow the user to focus on one floor at a time. Another possible solution would be to use location-based AR, freeing the user from the constraints of the image and enabling them to vary their perspective. Current generations of mobile technology allow for precise positioning using GPS and Wi-Fi signals, and researchers have been able to use that functionality to obtain locational accuracy within 4 m (Torres-Sospedra et al. 2015). While accurate, a 4 m error in position would have significant alignment implications for these visualizations. In time, positional accuracy will improve, allowing the viewer to move freely within the mixed reality environment to overcome these depth perception problems.

3.6.2. Situated AR for egress analysis

The situated AR development that we have presented in this paper represents a step forward by connecting computer based egress modelling with the real-world. The collection of sophisticated algorithms and software currently used for evacuation assessments and building safety classifications do what they were designed to, but the results are without real-world context. The emergency manager that states “we do not know what it would look like if everyone was forced to evacuate” will not find a comprehensive answer in mathematical equations or static visualizations. Recent additions to egress modelling have provided 3D visualization capabilities, but these visualizations remain disconnected from the real-world. Situating those simulations in the real-world with an AR interface provides a new level of visual representation and analysis, allowing that same emergency manager to begin to understand what that dynamic process would look like in real life.

The purpose of this research was to develop a workflow for situated AR-based analyses of human movement. The context provided by situated AR allows the viewer to compare the movement of people in the VE to the features of the landscape in the real-world. Those features are often omitted from evacuation assessments or are accounted for in attribute tables as static features with defined egress impedance values, and this workflow introduces a tool for situated visual assessment of their potential impact on simulated human movement. In the absence of real life exercises, or actual hazardous events, how is one to know what impact they might have?

3.6.3. Application of AR to egress analysis

The prototypes presented in this paper illustrate how situated AR could be used for egress analysis, but questions about their applied use and effectiveness remain unanswered. Simply put, just because you can does not mean that you should. The subsequent phases of this research will be focused on pragmatic field testing to assess the application of situated AR to emergency management. That testing will address the ability of these visualizations to improve user cognition and increase risk awareness. Studies on the usefulness of AR for wayfinding have seen mixed results, where the effectiveness is partially determined by personal preference and experience (Dünser et al. 2012). Our hope is that these tools prove beneficial as a supplement to current approaches of emergency management.

This research, and the development behind this set of AR tools for situated visual analyses of human movement, represents a continuation of our work on evacuation simulations. That research focused on the analysis of human movement using a desktop computer interface, and suffers from an inherent dissociation from the real-world. Research has shown that our reliance on satellite navigation technology has resulted in a spatial disconnection, suggesting that our reliance on spatial technology has left us unaware of our place in space (Speake and Axon 2012). These findings could hold true for emergency management, where one has conducted the computer simulations but does not fully comprehend how they relate to real spaces. Our goal with situated AR-based analysis is to bridge the gap and improve the user’s ability to comprehend the spatiality of the phenomena by situating the hypothetical in real environments.

3.7. Conclusion

This paper presented the research and development behind a collection of prototypes for augmented reality based situated geovisual analysis of virtual human movement in real space. We summarized some of the tools currently used in emergency management for egress analysis, and commented on the limitations associated with them. We highlighted their limited ability to capture the complex and dynamic geometries of the built environment that are relevant to emergency egress scenarios, and the resulting generalizations about human movement in complex spaces.

We suggested that new, situated 3D geovisual analytical approaches that dovetail with current GIS workflows are needed to connect simulated human movement with the real-world spaces they address. We introduced a series of situated AR-based simulation prototypes that allow emergency managers to assess the simulated movement of a building’s occupants from the building’s exterior, to evaluate the impact of obstacles on egress, to observe the flow of virtual evacuees down real corridors, and to compare simulated evacuation patterns against the real-world features that influence them. While these prototypes may seem like a novel technique for simulation and analysis, they provide the missing connection between virtual spaces of simulation and the real-world spaces of risk. The capacity to spatially contextualize egress analyses represents the first step towards closing the gap between abstract analyses, real-world cognition, and spatial knowledge transfer of risk.

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Chapter 4. Locational awareness in multilevel space: generating situated augmented reality based geovisualizations for spatially contextualized communication of evacuation plans[3]

4.1. Abstract

Preparedness is a fundamental component of emergency management that involves planning the response to hazardous events. In order to prepare people for potential risks and improve public safety, it is critical that emergency plans are communicated effectively. In multilevel built environments, that communication can be difficult, as the complexity of the architecture creates problems for both visual and mental representations of those 3D spaces. Modern mobile technology offers a platform with which emergency managers could provide 3D representations that preserve the topology of multilevel space, adding the spatial context that allows the individual to better understand their position within it. In this paper, we present a collection of cutting edge mixed-reality (specifically augmented reality) geovisualizations that overcome the visual limitations associated with the traditional, static 2D methods of communicating the evacuation plans of multilevel buildings. Using pre-existing building features, we demonstrate how this technology provides spatially contextualized 3D geovisualizations that promote spatial knowledge acquisition and support cognitive mapping. These geovisualizations are designed to help increase emergency preparedness and mitigate the evacuation related risks in multilevel spaces.

4.2. Introduction

The primary objective of any emergency management plan is to ensure the health and safety of the people. While there may be slight strategic variations between organizations, the foundation of those plans is typically formed around the core elements (mitigation, preparedness, response, and recovery) of the emergency management cycle. Regardless of what that plan is, or how it was developed, for the plan to be

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[3] A version of this chapter has been submitted to *Safety Science* under the co-authorship of Nick Hedley.

successful it must be effectively communicated to all those who are at risk. For indoor environments, that communication frequently involves strategically positioned notices of the emergency procedures, accompanied by a map that outlines those procedures in a simple visual depiction of that space. While there is a significant body of research that supports the development of emergency and evacuation plans, few have focused on the visual communication of that information. The traditional 2-dimensional (2D) maps which are relied upon to communicate the evacuation plans of these complex 3-dimensional (3D) built spaces, provide planar perspectives that are limited in their ability to advance spatial knowledge acquisition, spatial awareness, and therefore, public safety within built environments.

While evacuation maps aim to inform the reader about their position in space, they often challenge the reader's comprehension of where, exactly, they are. You-are-here; a simple, unassuming symbol or phrase that adorns countless evacuation maps can cause so much confusion. For single-floor buildings these you-are-here maps may be straightforward, as the mental connections between the visual depiction of the plan and the readers position within it, to the real-world space it represents, may be unchallenging. For multi-floor buildings, these maps can become extremely complex, often requiring the reader to connect their position above or below ground, to evacuation routes on disparate levels, in abstract mental representations of those spaces. We argue that the traditional 2D visualizations that represent these complex built spaces fail to properly contextualize those 3D spaces, and that supplementary methods of visualization are needed to improve spatial cognizance and emergency preparedness.

The objective of this paper is to present the research and development behind a series of mixed reality (MR) based geovisualizations that we have designed to support the current strategies of emergency evacuation communication. We review some of the existing methods for communicating evacuation information, focusing on their ability to represent complex spaces and promote cognitive mapping. We introduce MR as an emerging strategy for communicating geospatial information, and highlight how it has been applied across multiple disciplines to improve one's ability to reason with and better comprehend visual information.

4.3. Research context

As the world’s population trends towards densified urban living, and natural and manmade hazards become increasingly prevalent, there is greater potential for catastrophic events that impact large populations of people. Emergency plans strive to reduce the risk to these populations and evacuation plans attempt to guide people to safety, but the plans themselves serve little purpose unless they are communicated to the population facing those risks. In the absence of training, experience, or familiarity with a given space, maps are one method through which evacuation plans, and a variety of related geospatial information, can be communicated to the public (Dymon and Winter 1993). However, connecting the information presented on those maps to the real-world can be difficult, and if poorly designed, maps can leave the reader ‘confused and disoriented’ (Dent 1972). Maps serve a vital role in communicating geospatial information to the public; however, ubiquitous mobile technology provides the platform, and therefore the opportunity, for new perspectives, added dimensionality, and levels of spatial awareness that are difficult to achieve with traditional maps. In this section, we present research on the function of evacuation maps, the construction of cognitive maps, and the opportunity for mixed reality geovisualizations to change the way we conceptualize complex multilevel spaces.

4.3.1. Evacuation maps

An evacuation map is designed to inform the public of the evacuation plan. It is one of three map styles (planning, evacuation, and crisis) characterised as a type of emergency map (Dymon 1994). Evacuation maps for indoor environments are typically placed within rooms and along main transportation corridors, highlighting the position of the reader and the pathway to the nearest exit, with a primary objective of decreasing egress time (Teknomo and Fernandez 2012). Despite the reliance on these maps to communicate critical information, a comprehensive review of the theoretical research related to evacuation map design reveals little more than an agreement that there is a lack of research on the topic. Most of this research focuses on outdoor environments at regional scales.

The published research on evacuation maps suggests that a successful map is one that is easily understood and adheres to basic cartographic principles (Dymon and

Winter 1993; Chen, Zick, and Benjamin 2015). In times of crises, these maps should provide a clear visualization to the reader that allows them to situate themselves and find safety without having to decipher lengthy text or confusing visuals (Dymon and Winter 1993). However, in an analysis of the evacuation maps for areas surrounding 13 nuclear power stations in the United States, Dymon and Winter (1993) found that most failed to include basic map elements (e.g. a compass rose or legend), and in many cases, downplayed the risk by reducing the station's visibility on the map. The maps were not clear or easy to understand, and were further burdened by policy guidelines that required lengthy prose for those who could not understand maps. Their analysis concluded that the expected role served by evacuation maps was limited.

The evacuation map is therefore considered a resource for those that need assistance during an evacuation, and should not be used to educate the public about evacuation procedures. However, in the absence of the evacuation drills and exercises that have been identified as a critical component of emergency preparedness (Public Safety Canada 2010; FEMA 2013; University of Canterbury 2014, and others), there are limited resources or opportunities for educating the public about evacuation routes. Regardless of how clearly those routes are marked in the real-world, research indicates a reluctance to follow unknown pathways and a preference to retrace familiar ones, even if more direct routes to safety are available (Johnson 2005). This suggests that the cognitive maps (mental representations of space) that a building's occupants are relying on to navigate these spaces are incomplete, and that new methods of visualization, which promote higher levels of spatial cognizance, would be beneficial for improving emergency preparedness.

4.3.2. Cognitive maps

A cognitive map, or mental map, is a mental representation of an environment that one generates and stores in their head. When we are faced with complex spatial challenges, we call upon our memories of these environments, the mental maps, to provide a birds-eye perspective of that space (Taylor, Brunyé, and Taylor 2008). The idea of a cognitive map was first proposed in 1948 by American psychologist Edward Tolman, who theorized that rats, and by extension humans, develop mental representations of space that influence their behaviour in those environments. The idea of a cognitive map has since been widely adopted across the social sciences, resulting in contrasting definitions, and a contested trend towards wide-ranging use explaining all thoughts and behaviours related to spatial environments (Kitchin 1994).

While the definition of cognitive map varies across disciplines, so too do the theories surrounding the development of cognitive maps. Some research supports the idea of *associative* models which use the allocentric relationships between landmarks to codify space, while others support *positional* models that define the egocentric relationship of one's self to the spatial landmarks of a given place (Wang and Spelke 2000; Taylor, Brunyé, and Taylor 2008). Others report that cognitive maps combine allocentric and egocentric representations according to the specifications of the task and the environment for which they are referenced (Burgess 2006; Newman et al. 2007). Either way, the spatial knowledge necessary for cognitive map development can be obtained through direct interaction with real-world spaces, or through mediated interactions with visual representations of those spaces (Sharlin et al. 2009); irrespective of the source, a mental model is not the inevitable outcome (Taylor, Brunyé, and Taylor 2008). The process of configuring mental representations of space is a cognitive challenge, especially when those spaces are complicated multilevel and interconnected structures.

The scarcity of empty space, combined with the increasing human populations within and surrounding modern cities, necessitates vertical development characterised by increasingly large multilevel structures. These complex spaces can be frustrating, confusing, and difficult spaces to navigate, particularly when attempting to travel between floors (Li and Giudice 2012). Vidal, Amorim, and Berthoz (2004) suggest that the cognitive maps for these multilevel spaces are composed of a series of 2D mental representations connected by junctions, and that physical rotation in space accompanied by vertical displacement (e.g. stairwells) inhibits contiguous mental mapping. Without an external landmark (real or virtual) as a frame of reference, it is difficult for humans to mentally connect the multiple levels of complex spaces (Li et al. 2016). These examples illustrate how the experiential knowledge gained navigating multilevel indoor spaces fails to yield the general frame of reference (survey knowledge) required to comprehend spatial relationships throughout complex spaces. As survey knowledge can be attained using visuals (e.g. maps or models), there is an opportunity to employ 3D models and MR interfaces that add new perspectives which facilitate the viewers efforts to advance their spatial knowledge (Huang, Schmidt, and Gartner 2012).

4.3.3. Mixed reality

Mixed reality has become a hot topic in recent years, as new technology from Google, Microsoft, Apple, and Magic Leap (supposedly), promises to merge real and virtual worlds in fascinating ways. The concepts of *mixed* and *augmented* reality are not new, and despite the seemingly interchangeable use of the terms, they are not one and the same. Mixed reality describes technologies which merge real and virtual environments. It was first introduced by Milgram and Kishino (1994) to describe an emerging collection of visual display systems, that occupy the middle ground between entirely real and entirely virtual environments, on their “virtuality continuum.” They further subdivide MR as either augmented reality (AR) or augmented virtuality (AV), depending on the combination (proportions) of real and virtual content. The MR interfaces garnering recent attention add virtual objects to predominantly real-world environments, and are therefore examples of AR.

Augmented reality has many valuable applications beyond the gaming, social media, and marketing activities which have brought it into the mainstream. A review of AR applications by Billinghurst, Clark, and Lee (2015) highlights how the technology has been used by doctors to visualize the inside of the human body, by architects to see unfinished buildings, and by students to arrange virtual models of complex molecules in the classroom. These examples demonstrate how AR can be employed to help visualize that which cannot be seen, allowing the viewer to make sense out of abstract phenomena. Similarly, Hedley (2008) identifies a number of geographic applications for the visualization of spatial phenomena, and more specifically, the use of mobile augmented reality (MAR) to display virtual geographic information in everyday spaces. These in-situ visualizations hold tremendous potential for improving our ability to understand and navigate complex multilevel spaces.

A key component of AR interfaces is their ability to register virtual objects to real environments, providing the illusion that both occupy the same space. This ‘tracking’ is critical for navigation purposes, as the virtual guidance provided by the MAR application must align with the real-world environment to which it applies. Outdoor MAR navigation systems use GPS signals to register virtual information to the user’s position in space (Tsai et al. 2012; Dünser et al. 2012); however, indoor MAR systems cannot rely on GPS signals, alternatively using Wi-fi signals to provide the necessary positional tracking

(Torres-Sospedra et al*.* 2015). More recently, Google has developed a visual positioning service (VPS) for its Tango enabled devices that tracks the physical characteristics of real-world spaces and subsequently registers virtual information to them. Despite these advances, guidance systems may not be the best application of AR for emergency managers that are looking to increase a populations spatial awareness and overall safety.

While familiarity with space can produce the spatial knowledge used to generate cognitive maps, research has shown that GPS and automatic navigation systems do not improve spatial awareness (Huang, Schmidt, and Gartner 2012; Speake and Axon 2012), and that these systems can create 'passive operators' with a degraded ability to acquire spatial knowledge (Parush, Ahuvia, and Erev 2007). If AR is to be applied to emergency management with the purpose of improving spatial awareness, it must enhance to the user's ability to comprehend the topology of complex multilevel spaces by providing allocentric representations of space instead of egocentric guidance through space.

4.3.4. Contextualizing built spaces using AR

The 2D you-are-here maps that are commonly used within multilevel structures provide static, disjointed, and often restricted representations of complex multilevel spaces. While we do not dispute that these maps serve a purpose for public safety efforts, we argue that supplementary methods of visualizing these spaces are necessary for delivering the spatial context that is required to improve spatial awareness within complex structures.

In the preceding sections, we emphasised how evacuation maps are meant to inform evacuees in times of crises, providing a quick reference that helps them better understand the space and evacuate from it. We discussed how people rely on cognitive maps to navigate space, and that creating these mental maps in complex multilevel structures can be challenging, often resulting in fragmented mental representations of those spaces and a preference to evacuate via the familiar, rather than the quickest or safest, path. While evacuation exercises are important, it is impractical to suggest that these exercises can be conducted by all people, from all possible locations within a building. In the following sections, we present the workflow behind a collection of AR geovisualizations that supplement the existing campus maps, signage, and evacuation plans at Simon Fraser University (SFU), Canada. Our objective is to highlight how AR-based 3D evacuation visualizations, situated and specific to real spaces, can encourage spatial knowledge acquisition and cognitive mapping in complex multilevel buildings.

4.4. Methodology

We present here a collection of innovative AR prototypes for the visual communication of emergency evacuation information in a complex institutional space. The objective of this research is to demonstrate the application of MR interfaces within the realm of emergency management. This research builds upon our previous emergency evacuation research that explored game-engine based evacuation simulations situated in real and virtual spaces. While those papers addressed the influence of space on evacuation behaviour, we here explore a new communication strategy with the potential to improve spatial awareness and influence evacuation behaviours in multilevel spaces. In the following sections, we describe our workflow, including the hardware/software used to develop these visualizations.

4.4.1. 3D assets

Our AR visualizations are focused on the visual communication of 3D geospatial information. We describe here a workflow that combines 3D GIScience with 3D modelling and a 3D game-engine to produce these 3D visual assets.

SketchUp

The 3D model of SFU’s Academic Quadrangle (AQ) that is used in these visualizations was built with SketchUp design software. An architectural drawing (.dwg file) for each floor was imported into the software and the 3D structure of the building was extruded from those 2D drawings as per their specifications and GPS measurements of building features. SketchUp was also used to create the 3D assets representative of the evacuation pathways in the first two AR examples. Both the 3D building and the evacuation pathways were exported as 3D Object files (.obj). The 3D model of SFU used in the campus wide evacuation map was provided by SFU Facility Services, but was modified in SketchUp to focus only on main campus buildings. The evacuation pathways and labels were added to this model by the authors.

CloudCompare

CloudCompare is an open source 3D point cloud and mesh processing program that was used to build the 3D surface model presented in example three. The LiDAR point cloud and high resolution image used to create this model were provided by SFU's Spatial Information Sciences department. The 3D model was clipped to its current extent, and textured, using Autodesk Maya.

ArcScene

The evacuation pathways presented in example three were derived from a 3D network analysis conducted in ArcScene. That network analysis calculated the five exits nearest to the location of the evacuation sign used as the AR image-target. The 3D shapefiles for those network segments were exported from ArcScene as 3D assets (Object files) using the Data Interoperability extension.

4.4.2. Mobile deployment

The visualizations that we present here were tested on Android enabled mobile devices and could easily be adapted for Apple or Windows based hardware. Our choice of operating system is simply a reflection of the available technology and the developer permissions associated with it. Our prototypes were tested on two Samsung Galaxy mobile phones (S4 and S7); this hardware has specifications which are typical of modern smartphones. These mobile devices provide a compact, yet powerful operating system for the software, and are equipped with the high-quality cameras required for image-based AR.

4.4.3. Augmented reality

The prototypes that we have developed are examples of image-based AR (also known as *tangible AR* or *marker-based AR*), which uses computer vision software to recognize defined images, and subsequently renders virtual objects on the display system relative to the position and orientation of those images in space. One of the most common forms of AR image is a coded black-and-white design similar to a QR code (Cheng and Tsai 2013); however, our prototypes use what is known as *natural feature tracking*, where the software has been designed to recognize visual patterns in the real-world based on photographs of those features (Hedley 2017). This workflow would allow emergency managers to supplement existing infrastructure without having to modify it.

Our first two examples were developed for Augment, a third-party AR application for mobile devices. In these examples the 3D virtual objects were uploaded to a web based database, where they are then available for download directly to any mobile device operating the Augment software. Each virtual 3D object is associated with a specific real-world feature at SFU (room number, hallway marker, or campus map). Our third example was built with Unity, an open-source game engine, and the AR software development kit (SDK) offered by Vuforia. Our prototype application was built on PC and deployed directly to the authors Android smartphones. This software was pre-programmed to recognize a specific evacuation plan sign at SFU; however, similar evacuation signs could be augmented with their own unique AR datasets.

4.5. AR geovisualizations

This research is focused on developing a workflow and a series of prototype visualizations that enable the visual analysis of evacuation information, situated and specific to the location from which it is viewed. Our objective is to highlight how AR display technologies can be used to contextualize complex spaces by providing interactive 3D visualizations that connect those spaces, both within and beyond the confines of multilevel buildings. These visualizations serve as an example of a technique for presenting information about complex built spaces that preserves the dimensionality of that information, encouraging cognitive connections between the abstract and the real-world. We describe the specifics of those geovisualizations in the following subsections.

4.5.1. AR example #1: campus maps

Our first AR visualization was developed to provide general campus wide evacuation information for SFU. The scene contains 3D representations of the exterior profile of every major building on campus, labelling each with distinct 3D block text, and illustrating the general evacuation pathways from each building to a safer location (Figure 4.1). The objective of this visualization is to illustrate how analogue maps, fixed in their form and function, can become the foundation for interactive AR displays. With AR, the theme of any analogue map is no longer static, as each can be visually augmented with additional information and dimensionality. This visualization can be operated on any mobile device containing the Augment application.


Scan an image with the Augment logo or a QR Code.

Figure 4.1 Augmented Maps
Spatial data in a GIS is presented as a series of layers. Each of those layers can be turned on (is visible) or turned off (is not visible). When the map-maker publishes a paper map, they define the visible layers of that map. However, with mobile augmented reality applications, those paper maps can become the foundation for GIS-like interfaces that allow users to add additional layers to the map. In this case, the campus map at SFU is augmented with 3D models of the buildings on campus and potential evacuation routes from them.

In this example, the 3D data and an image of the campus map were uploaded to the Augment database, where that image was then registered as the image-target used by the software to position and display the 3D data on the mobile device. When the user has installed the application on their device, they simply open that application, point the device's camera at any copy of that campus map, and the software scans the real-world for the visual characteristics of the image registered in the database. When those visuals are detected, the 3D data is rendered on the device's display. The user can then manipulate the position and orientation of that data directly on their screen, or they can explore the data by adjusting their (camera) position relative to the campus map.

This visualization was designed as a method for informing regular campus citizens and visitors about the evacuation procedures on campus. To our knowledge, there are no maps, or other visuals, that outline campus wide evacuation plans for those at SFU. In a complex built space such as SFU, where multiple buildings are interconnected, and one building's exit may place you on the roof of another building, it is important that people understand the topology of space and the implications for safe evacuation pathing. We feel that AR provides an effective method of communication that extends the capacity of current infrastructure without having to increase the complexity or quantity of campus maps.

4.5.2. AR example #2: evacuation routes

Our second example is a set of AR visualizations which illustrate how AR can be employed to provide situated evacuation information. These two visualizations contain a 3D model of the AQ, and the evacuation pathway from the viewer's location to a designated muster site (Figure 4.2). The objective of these visualizations is to illustrate how AR can provide location specific geospatial information that encourages the cognitive connection between the presented information and the viewer's location within that space. With these visualizations, the viewer is granted additional context in the form of a 3D representation of the entire building (not simply the floor they are on), an evacuation pathway out of that building (not the nearest stairwell or junction), and a suggested path to a muster site (not an assumption that outside of that building equates to safety).

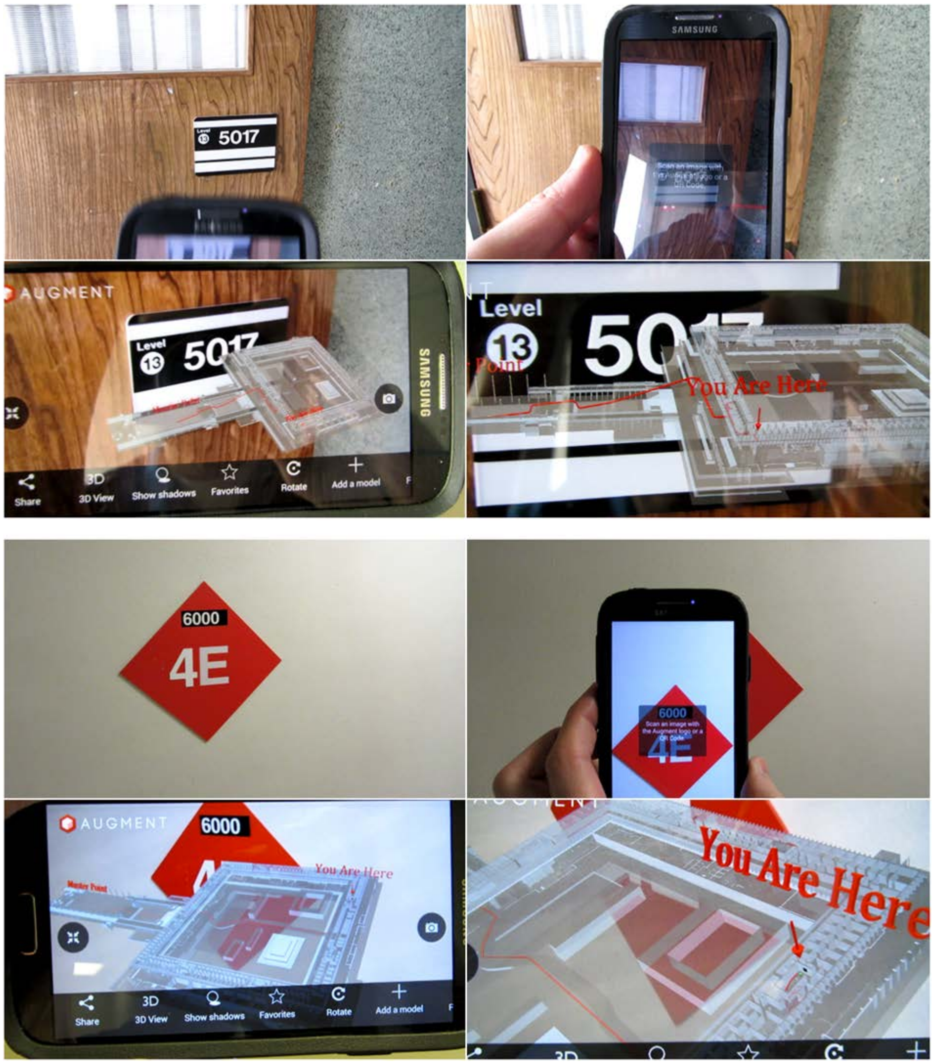

Figure 4.2 Augmented Signs
The existing visual features of a building can become the targets (markers) for situated mobile AR geovisualizations of the evacuation route from that location. **(top)** Each room at SFU is identified with a unique room number, and each of those room numbers provides a unique visual feature that can be used as an AR target. **(bottom)** Other signage around campus, like this stairwell marker, provides a unique visual feature for situated AR.

These visualizations operate using the same Augment application introduced in example one, and follow a similar workflow. However, instead of using a campus map for AR registration, these examples were designed to illustrate how the visual features of inconspicuous objects within a building could become the platform for situated 3D visualizations. In the first instance, we used the room number outside of a classroom, and in the second we used a sign identifying the floor number and location of a stairwell as the visual features for AR registration. Distinct visual targets like these are common across the SFU campus and within multilevel structures, providing opportune platforms for the delivery of situated geospatial information.

The inspiration for the visualizations in this example stems from an apparent lack of evacuation drills at SFU. In the absence of these exercises, people on campus are left to rely on their cognitive maps, or the cognitive maps of others, to evacuate buildings. With the complex architecture characteristic of SFU, those cognitive maps may be disjointed and incomplete representations of space. The 2D maps presented on the campus evacuation plans only provide a snapshot of these spaces, while these augmented views were designed to encourage the development of a more complete mental representation. They are not meant to replace those evacuation maps, or to be relied upon in times of crisis, but to be used as a tool for developing greater spatial awareness in complex built spaces.

4.5.3. AR example #3: evacuation plans

Evacuation plans are designed to inform people about the evacuation procedures for a given space. While there are few scientific research papers dictating, or evaluating, the design or content of evacuation plans, these plans are an essential component of emergency preparedness that can be found in most public spaces. The evacuation plan posted within SFU's AQ provides a written description of the emergency procedures and a simple 2D map of the evacuation plan that is specific to the location where that sign is posted (Figure 4.3). The map specifies the viewer's location (you-are-here), as well as the location of the exits, assembly area, and other emergency related features. That plan also suggests an evacuation route. However, the evacuation plan fails to provide the viewer with sufficient spatial context, and demands they connect their mental representation of space with an outdated map that is missing critical infrastructure updates (a new building is now located on the evacuation route). In this example, we present a prototype AR interface for communicating evacuation plans.

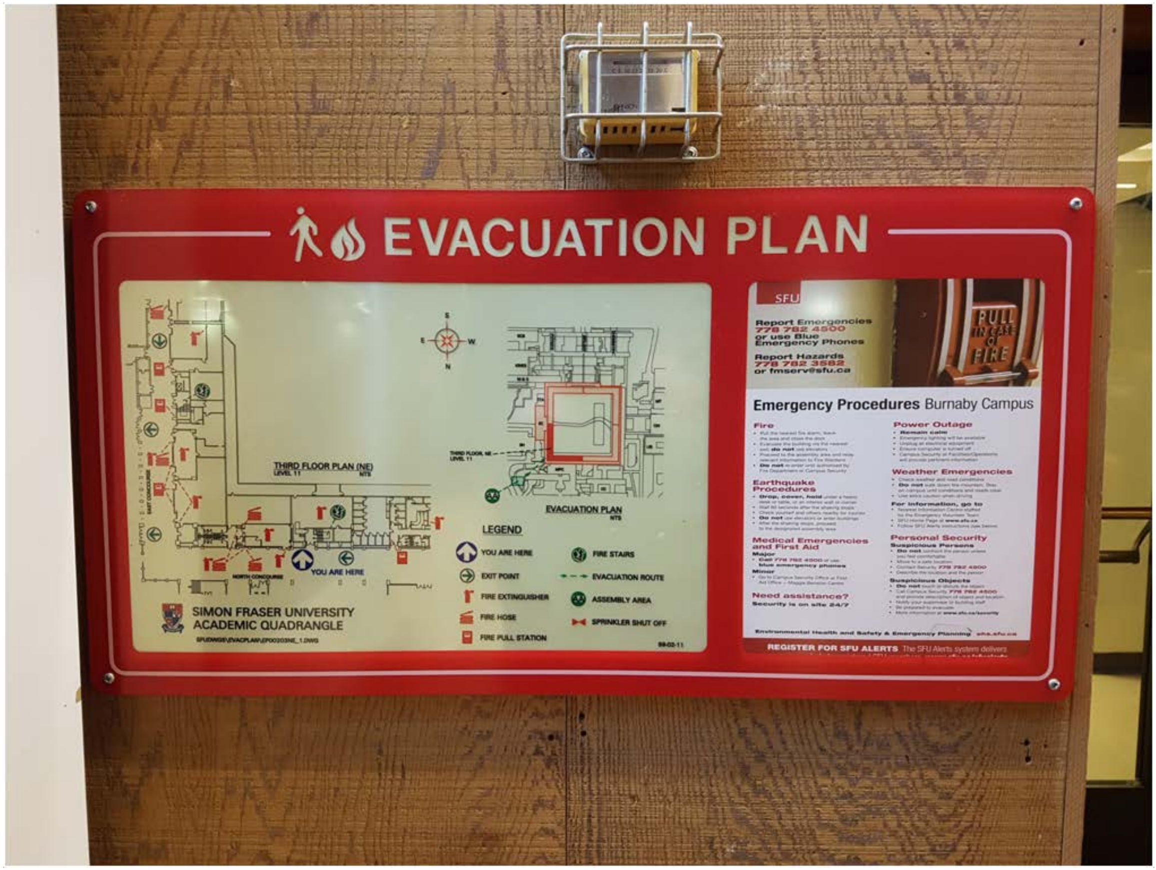

Figure 4.3 Posted Evacuation Plans

Posted evacuation plans provide a quick overview of the evacuation plan and a limited amount of spatial information. They are designed as a quick reference to help those who are unfamiliar with a building, or are lost, evacuate the building. When that building contains multiple levels, the 2D visual representation on that plan provides an incomplete representation of that space. Without additional spatial context, the reader does not know whether the indicated exit points provide a direct route to safety.

The AR interface presented here is a custom designed mobile application that augments the evacuation plan with additional 3D geospatial data. It was developed with Unity and the AR SDK from Vuforia, and was installed on the authors smartphone (Galaxy S7) using the Android and Java development kits. A photograph of the evacuation plan was converted into an AR image-target using the Vuforia Developers Portal. AR content is displayed on the mobile device when the user points the device camera at the evacuation plan posted on the wall (Figure 4.4). In the following subsections, we discuss the different methods of displaying AR content within our prototype application.

Figure 4.4 Augmented Evacuation Plans

The evacuation plans posted within a building serve an important role; however, they provide a limited amount of information and should not be relied upon to educate a building's occupants about the evacuation plan. As AR targets, the richness of spatial information associated with those evacuation plans can be greatly improved.

Nadir

The first visualization provides a top-down perspective of a 3D model that covers the same region, and supplies the same information, as the 2D evacuation map on the evacuation plan (Figure 4.5). When the model appears on the screen it is aligned to match the evacuation map. The user can rotate that model and adjust its scale using the sliders on the graphical user interface (GUI). The user can also manipulate their perspective by adjusting their (mobile device camera) position relative to the evacuation plan.

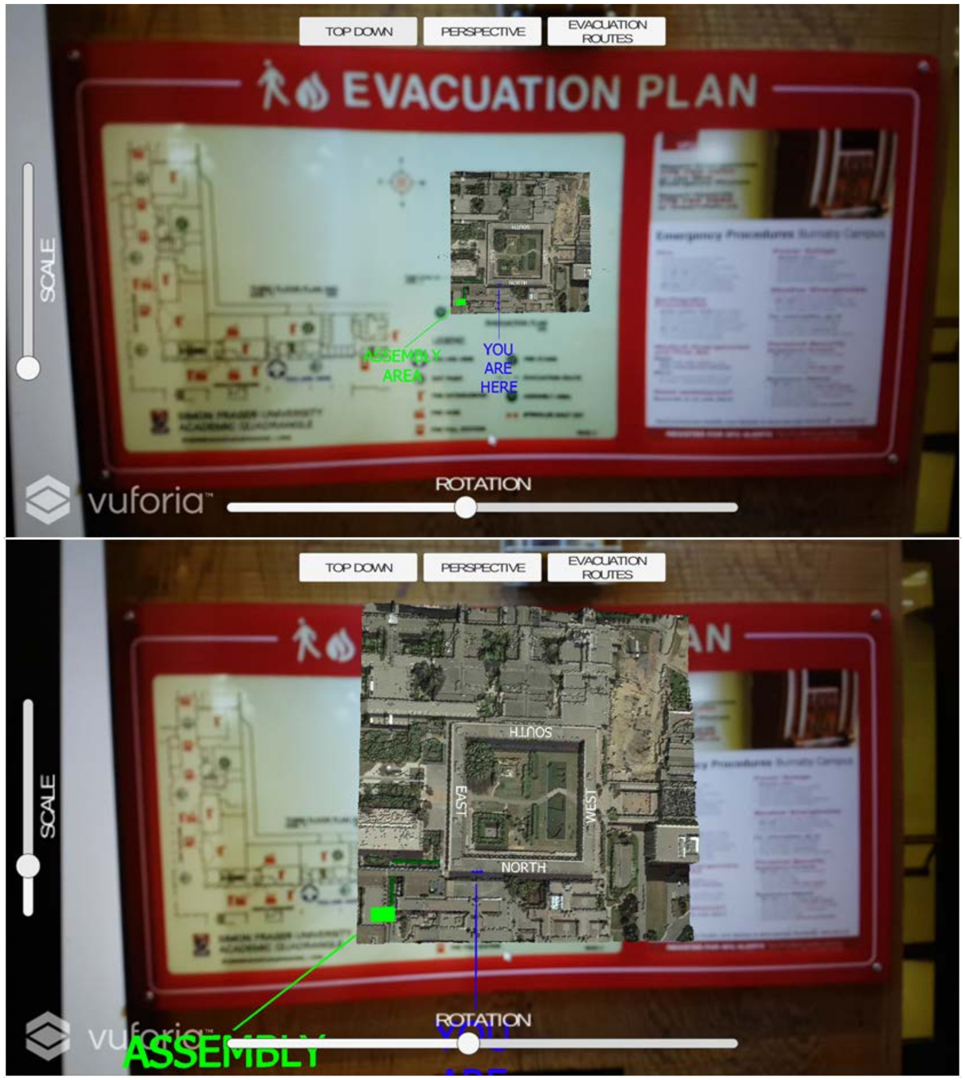

Figure 4.5 Nadir AR
The posted evacuation plan provides a crude map indicating the viewers position, the assembly area, and the suggested path to it. An augmented view of that map provides additional spatial context, in this case allowing the viewer to see that the suggested evacuation pathway is now obstructed by an additional building. The viewer can interact with the 3D model using their mobile device and the GUI.

The objective of this visualization is to provide a visual depiction of the space that is less abstract. The added dimensionality and aerial imagery may help provide context that better matches the user's mental representation of that space, and different visual perspectives may help trigger cognitive connections between data and place.

Off-nadir

The second visualization utilizes the same 3D model as the first example, only this time the spatial orientation of the model is aligned with the real-world (Figure 4.6).

The user can manipulate the scale and rotation of the model with the GUI; however, by aligning the 3D model with the real-world we remove the need for mental rotation, an unnecessary cognitive load that can cause viewers to misinterpret the data (Lonergan and Hedley 2015).

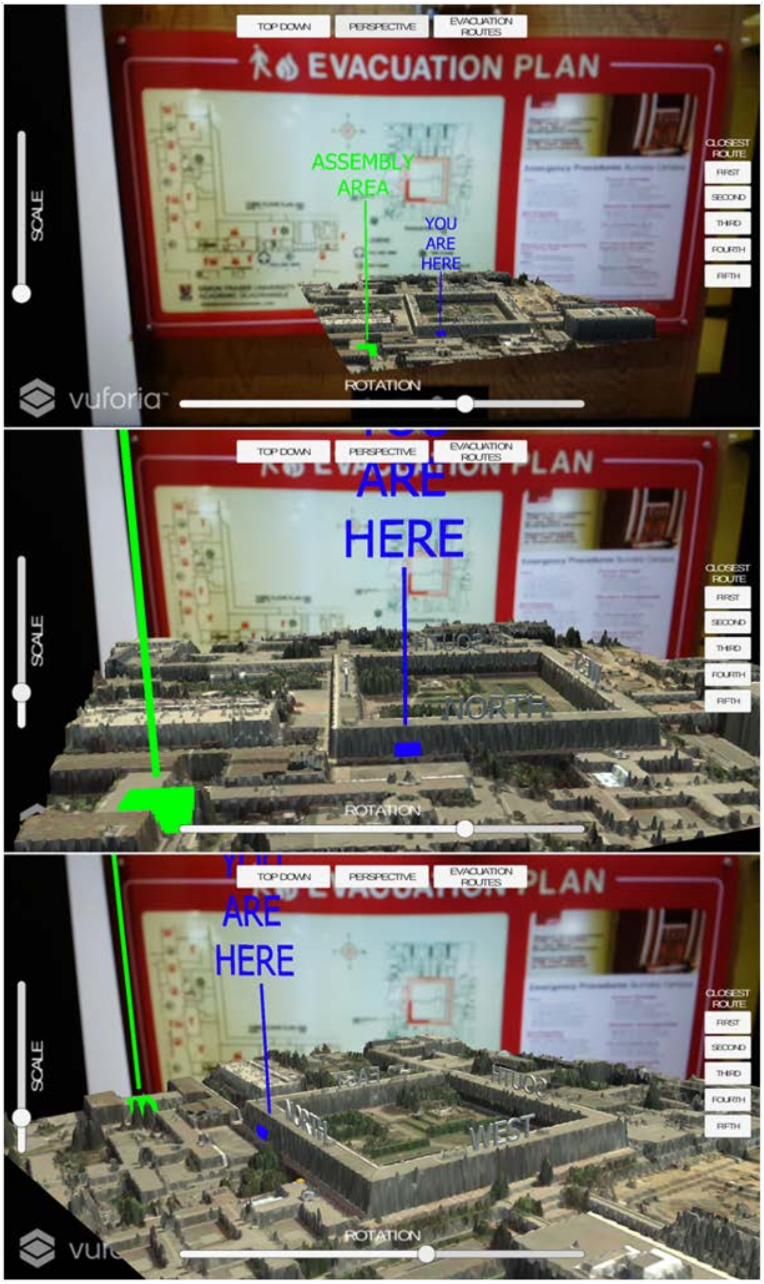

Figure 4.6 Off-nadir AR

(top) When an evacuation map is posted on the wall, the viewer must perform a mental rotation to align that map with the real-world. In this case, the AR application aligns the 3D model with the real-world, reducing the cognitive load of the viewer. **(middle)** The size of the model can be changed using the GUI. **(bottom)** The model can be rotated, allowing the viewer to change their perspective. These interactions help the viewer make sense out of the presented information and connect it to the real-world.

An added GUI feature of this interface allows the viewer to explore the location of the five emergency exits closest to the viewer's position as defined a by our 3D GIS network analysis (Figure 4.7). While the 2D map on the evacuation plan does indicate the location of exits, it does not provide spatial context that allows the viewer to understand the conditions outside those exits. The objective of this visualization is to provide a platform that allows people to better understand their position within the AQ, relate that position to physical features on the outside, and improve their ability to evacuate the building and find safety.

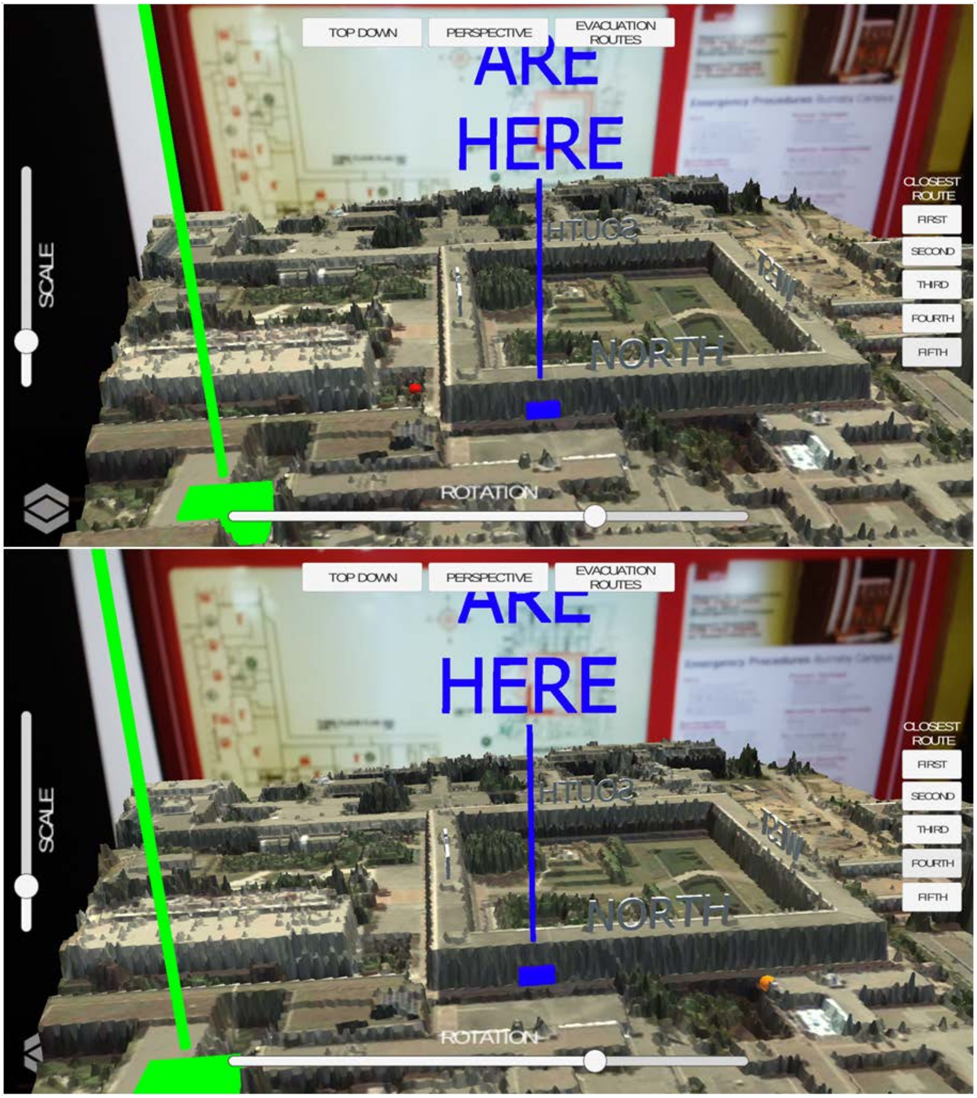

Figure 4.7 Contextualizing Emergency Exits
The posted evacuation plan indicates the location of the exits that are in close proximity to the viewer, but it does not provide the spatial context which would allow the viewer to make an informed decision about the safety of those exits. When augmented with 3D models, the viewer is provided with that additional context.

Transparent

Our final example adds a 3D model of the internal features of the AQ to the visualization. The entire model is rendered as a transparent mesh, allowing the viewer to observe the evacuation pathways from their position within the building to the five exits identified in our 3D GIS network analysis (Figure 4.8). The interface maintains the same GUI controls that allows the user to adjust the scale and spatial orientation of the model, and to selectively display the five evacuation pathways.

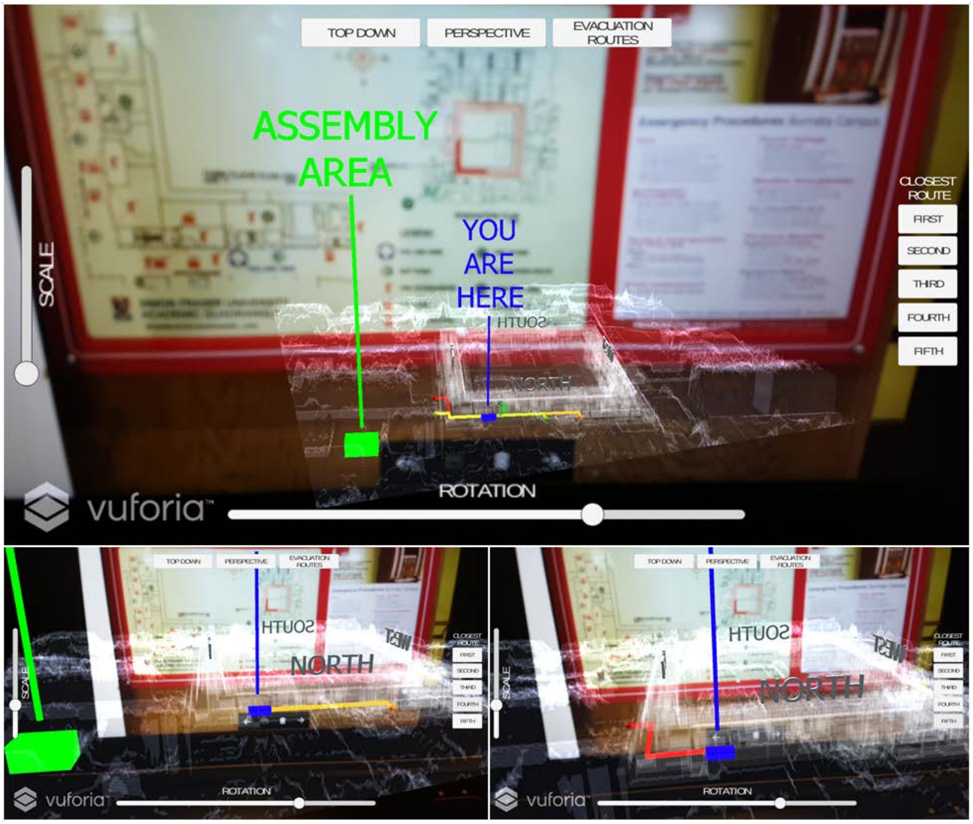

Figure 4.8 Contextualizing Evacuaiton Pathways
Providing spatial context for the evacuation plan of a multilevel building requires details about the topology of 3D space. In this instance, the closest exit is not on the same floor as the viewer, but one floor above. Using AR, the evacuation pathway can be displayed within a transparent 3D model of the building. The viewer is then able to formulate new spatial knowledge concerning their position in that multilevel space and its relation to the outside (safety).

The objective of this visualization is to add context to the evacuation pathway. Without context, it is extremely difficult to know whether the exit by the stairwell is on the same level, up one floor, or down two floors from the viewer. The transparent nature of the 3D model in this example allows the viewer to understand that the closest exit can be accessed on the floor above through the nearby stairwell.

4.6. Discussion

The examples presented in this paper demonstrate how AR might be used to facilitate spatial knowledge acquisition in complex spaces. We presented AR as a tool for communicating and learning abstract spatial information; not to be used in response to an emergency, but as a communication strategy for increasing emergency preparedness and public safety. In this paper, we used emergency evacuations as a framework to illustrate how AR technology can be applied to multidimensional network problems; however, AR holds great potential as a tool for communicating an array of geospatial information. In the following sections, we discuss the affordances provided by AR and the limitations that were observed during the development and testing of these evacuation visualizations, and conclude with a recommendation for future research.

4.6.1. Affordances of AR

Augmented reality, quite simply, is a display technology. It is a way to view computer-generated stuff. The value of augmented reality lies not in what it allows us to see, but how it allows us to see it. Azuma (1997) noted that AR enables what Fred Brooks called *intelligence amplification*: using a computer to make things easier. The process of creating a mental model of a multilevel space, and then connecting abstract information to that space, is a cognitive challenge. As presented in this paper, AR is a tool that simplifies that connection by providing visuals that maintain the dimensionality and continuity of multilevel space and the abstract information that relates to it.

Nevertheless, it is not the visualization itself, but the way that one interacts with that visualization that makes AR a powerful learning tool. Shelton and Hedley (2004) suggest that it is the visual, spatial and sensorimotor feedback provided by interacting with the AR interface that drives knowledge acquisition. The ability to explore and physically interact with abstract or complex phenomena is therefore critical to improving our understanding of them. This is supported by research on the use of AR to teach anatomy, where AR interfaces were found to improve the overall understanding of complex human systems while decreasing the cognitive load on the students learning them (Kujukk, Kapakin, and Goktas 2016). Similar sense-making AR interfaces would be beneficial for those attempting to comprehend the complex networks of multilevel structures.

4.6.2. Limitations

Augmented reality has proven to be a valuable tool for the visual communication of complex, and often abstract, phenomena. The quality of those visualizations is defined not by their visual fidelity, but by how clearly they communicate information and how well they support knowledge acquisition. As we developed these visualizations we identified key limitations associated with the software and the method of interacting with the visual content.

The visualizations that we introduced in this paper were deployed to either a third-party or custom-built mobile application. While there are several AR applications on the market that are capable of displaying 3D buildings and evacuation information, we wanted to highlight the limited functionality of those platforms as learning tools. Many are designed as marketing tools, or as a novel way to supplement some consumer product with virtual information. The software can handle animations, and allows the user to manipulate the size and position of the content, but each image is associated with one data set, and it lacks the interface controls that facilitate higher levels of interaction and analysis. The final set of visualizations, developed with Unity, provided a more GIS-like experience that allows the user to activate different layers and switch between data products (all of which were registered to the same image-target).

Despite this onscreen interaction, the position of the image-target used in each of these examples was fixed in space. Tangible AR, or AR that allows the user to pick-up the image-target and interact with the virtual content (Hedley 2003), increases the level of interaction and promotes investigation and sensemaking. However, increased interaction is a double-edged sword, as the ability to manipulate the image-target reduces the developer's ability to align the virtual content with the real-world, which degrades the connection between abstract information and the real-world.

4.6.3. Application to emergency management

Our research demonstrates that AR visualizations could be used to supplement the existing emergency communication strategies in built spaces. Whether it should, remains to be answered. Further research is required that tests the capacity of these visualizations to communicate geospatial information in a way that increases the viewers spatial and emergency cognizance. The next stage of this project will be to conduct those empirical tests.

The simple existence of AR applications for emergency management and public safety activities does not equate to their adoption by the general public. Much like the maligned QR code, AR technology requires special applications and additional effort from the user. We are not yet at a point (although it may seem like it) where the real-world is intertwined with a virtual one. However, if AR devices that continuously occupy our field of view become integrated with our daily life, and we are in fact about to realize the death of the smartphone and the rise of the cyborg, AR interfaces such as these will become much more prevalent. Until then, interfaces such as these could serve as a guided educational tool for improving public safety in built spaces.

4.7. Conclusion

This paper presented the research and development behind a series of prototype AR geovisualizations for the communication of emergency evacuation information situated and specific to real-world spaces. This work serves to highlight the ability to represent complex multilevel spaces in their inherently 3D form using AR technology. We discussed the importance of emergency preparedness and the role of evacuation maps, the challenges associated with cognitive mapping in complex built environments, and the ability to display, interact with, and explore abstract information using AR interfaces. We then introduced a series of AR geovisualizations that were designed to contextualize built spaces, to encourage spatial awareness, and to provide emergency managers with a tool for improving emergency preparedness and public safety.

Augmented reality is an emerging technology that has the potential to transform the way we interact with information about the built environment. The 2D maps that characterize these spaces, and which currently form the foundation of our mental representations of them, could be used as a stepping stone towards interactive 3D representations that encourage greater levels of spatial awareness in multilevel space. We hope that others take this research as inspiration for future applications of AR in emergency management, not to blindly guide us through space, but to better develop our understanding of space in an effort to improve public safety.

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Chapter 5. Conclusions

5.1. Summary

My objective with this thesis research was to advance the analytical and communicative capacity of emergency management using a succession of 21st century geovisualizations. The collection of interfaces presented in this thesis combine geographic information science and systems with 3D modelling, 3D game engines, artificial intelligence (AI), mixed reality (MR), and geovisualization.

This thesis contains three independent pieces of research which are focused on the analysis and awareness of evacuation based human movement within multilevel built environments. Each of these research papers employs a cutting-edge and non-traditional approach to geographic information science and emergency management, while maintaining rigorous spatial representation and analytical standards. The outcome of this research is: a new workflow that addresses the challenges of adequately capturing the geometry and topology of complex institutional spaces, while enabling the analysis of simulated human movement in spatially rigorous 3D virtual environments (VEs); a fundamentally new approach to AI based evacuation simulations which connects virtual evacuees with real-world spaces for situated analytics; and a framework for generating MR enabled geovisualizations for contextualized communication of evacuation plans within multilevel structures.

Chapter 2 addresses spatial representation as an important influence in the outcome of emergency evacuation calculations. I highlight how the network analyses of a 2D geographic information system (GIS) differ from those of a 3D GIS, and from those of a contiguous 3D network in a dynamic VE. I developed a 3D VE equipped with AI based agents and physics enabled obstacles, and demonstrated how it could be used to simulate and analyze human movement in built spaces. Additionally, I employed Structure from Motion (SfM) to produce 3D representations of interior space, illustrating how the complexity of those spaces impacts human movement.

Chapter 3 presents a framework that expands on the analytical capabilities of 3D VEs using mobile MR. I introduced a series of situated MR geovisualizations that allow emergency managers to visualize simulated human movement in real space. Situated analytics enables the visual analysis of projected egress against the physical features of the real-world. The main objective of this research was to demonstrate how MR could be used to add context while overcoming the challenges associated with capturing (modelling) the complexity of built spaces in their entirety.

Chapter 4 explores mobile MR as a tool for communicating and visualizing evacuation plans in complex multilevel environments. I produced a series of geovisualizations using third-party MR software and a purpose-built MR application for mobile devices. The objectives of this research were to highlight the issues with 2D representations of 3D topology, the challenges associated with creating 3D cognitive maps from 2D representations, and the opportunity for MR to influence spatial awareness with contextualized 3D representations of built spaces.

5.2. Research contributions

The research that I have presented in this thesis makes contributions to the fields of geographic information science, geovisualization and emergency management. While the methods I present in each paper may be non-traditional, each approach leverages critical theories and the importance of spatial rigour to produce a 21st century toolset that advances evacuation simulation, analysis, and communication.

Chapters 2 and 3 make the most significant contribution to this thesis. They merge the spatial science of GIS with the simulation capabilities of game development software, capturing the complex interactions between people and built spaces during the evacuation of a building. I have situated this research in the fields of GIS, emergency management, game development, and visualization to highlight the multidisciplinary nature of the problem and the benefit of a non-traditional approach to solving it. Traditional evacuation simulation software addresses emergency egress from the perspective of performance based building codes and regulations (Tavares 2009). The approach presented here overcomes the limitations those systems have in regards to dynamic scenarios, dynamic environments, and visual outputs for analysis and communication of the process. These VEs offer interactive, customizable interfaces to expand the capabilities of emergency managers.

Chapter 4 reports on a set of new MR prototypes that demonstrate the potential of annotating everyday spaces with emergency evacuation information. The objective of an evacuation plan is to ensure that everyone overcomes their exposure to risks as fast as possible, and I argue that the best way to ensure the expeditiousness of that process is through education. While others have explored MR as a navigation aid (Tsai et al*.* 2012; Dünser et al. 2012; Torres-Sospedra et al*.* 2015), I argue there are risks associated with creating 'passive operators' who blindly progress through space without developing any mental representation of it (Parush, Ahuvia, and Erev 2007). MR provides an interactive visual interface that is influential in knowledge acquisition (Shelton and Hedley 2004), and it is employed here to encourage spatial awareness and evacuation cognizance in multilevel buildings.

5.3. Future directions

This research represents the foundation for future geovisualization research associated with emergency management. The VE presented in Chapter 2 is capable of larger, more complex simulations that incorporate more buildings and AI agents, but could also be used to capture and visualize the behaviour of a given population. Emergency simulations seek to provide a best estimate of how a population may behave, and the characteristics of the AI agents within those simulations are generalizations of evacuation behaviours which the program uses to conduct the simulations. There are two possible directions for future research within this VE: 1) place people in the simulation using desktop and virtual reality interfaces that allow them to control the agents; and 2) collect risk perception and behavioral data from people in the study area and use that to control agent behavior.

The MR interfaces presented in Chapter 3 provided a workflow and demonstrated how the technology could be applied to virtual evacuation analyses situated in real-world spaces. There is potential to further develop these applications with an advanced graphical user interface (GUI) that allows emergency managers to control the conditions of the scenario (e.g. number of evacuees, type of hazard, location of hazard). Additionally, with higher accuracy positioning, the application could be developed to use location based MR, providing greater freedom for the viewer to change their perspective on the simulation.

Chapter 4 introduced new MR prototypes that bring virtual evacuation information into everyday space. There are several opportunities to expand the scope of these geovisualizations, including: MR visuals of the evacuation plans overlaid on real-world features; additional MR functionality (e.g. animations or walkthroughs); advanced GUIs; and, tangible MR interfaces that permit additional interaction and visual inspection. However, it is imperative that these prototypes undergo an empirical study of their efficacy as a communication and learning tool prior to any of these additions.

Each of the geovisualizations presented in this thesis would benefit from user based empirical studies. Future research should test the functionality of the applications in addition to their performance as emergency management tools. The VE presented in Chapter 2, and the MR prototypes from Chapter 3, should be tested with emergency managers. The MR applications from Chapter 3 should be tested on emergency managers as well as regular citizens.

In conclusion, the research presented in this thesis advances the capabilities of emergency managers by incorporating the theories and practices of GISystems, GIScience, 3D modelling, game development, and geovisualization with those of emergency management. Each chapter illustrates a unique approach to a spatial problem, providing a workflow and demonstrating their visual and analytical capacity as tools to improve emergency management efforts. Furthermore, each chapter serves to progress the fields of GIScience and geovisualization with new applications and demonstrated efficacy. Both as standalone research papers, and as a collective approach to 21st century emergency management, this thesis aims to inspire and inform future efforts to improve emergency preparedness and build risk resiliency.

5.4. References

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