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Proof-of-Concept: Safety Hazard Identification and Impact Minimization Using 3D BIM and VR Devices Through the Case-Studies

Sudeep Pangeni

PROOF-OF-CONCEPT: SAFETY HAZARD IDENTIFICATION AND IMPACT MINIMIZATION USING 3D BIM AND VR DEVICES THROUGH THE CASE-STUDIES

by

SUDEEP PANGENI

(Under the Direction of Marcel Maghiar)

ABSTRACT

Construction hazard is a global issue. Despite numerous research studies, safety guidelines and procedures, fatalities and severe injuries still occur on construction job sites. This research has been performed to identify the research gaps and potentially improve worker behavior along the most hazardous tasks during construction execution using 3D Building Information Modeling (BIM) and Virtual Reality (VR) devices. A safety hazards-related questionnaire for civil engineering and construction students, superintendents, safety, and project managers across six different states including the state of Georgia was deployed. The questionnaire was distributed via an online platform to identify and approach the hazards which occur during the pre-construction design and are latent until the execution of a project. Through a case-study, qualitative, and quantitative-based analysis, the study aims to investigate many hazards that remain unidentified using 3D BIM models and integrating them through VR devices. The research focuses mainly on electrical, mechanical equipment, roofing, and concrete works during the project execution. The chi-square test was used to examine the variability of the independent factors' hazard recognition performance when they were crossed with the dependent variables (i.e., safety training, technology usage/advanced device training) to test the hypotheses. The study's findings and recommendations can be utilized by construction organizations to evaluate BIM and VR adoption and decide whether and how they should be used for hazard detection and impact mitigation. In order to emphasize on accident causation and the significance of thorough hazard recognition and appropriate risk perception, researchers created a virtual walk-through replicating acceptable actions in close proximity to specific activity risks into a VR environment. Suggestions are also made to improve course design for any construction safety training by looking at the impact of BIM in conjunction with VR on construction safety and hazard mitigation.

INDEX WORDS: Building Information Modeling (BIM), Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Construction safety, Hazard identification, Hazard-impact minimization, Virtual Design and Construction (VDC), Construction execution

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SUDEEP PANGENI

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SUDEEP PANGENI

Major Professor:	Marcel Maghiar
Committee:	Gustavo Maldonado
	Soonkie Nam

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DEDICATION

The completion of this work was possible with the help and support of my family and friends. I dedicate this work to my parents (Baba & Ama), who always sacrificed and motivated me to pursue my desired career. To my lovely sisters, Trisha, and the entire rest of my family who encouraged me throughout the difficult times and motivated me to achieve this dream. Finally, a big thank you to my friends: Nilkantha Neupane, Bhanu Bhakta Aryal, Subash Ghimire, Neeraj Pudasaini, Pitri Acharya, Arjun Subedi, Dhurba Sunuwar, Upal bhai, and many others who helped and supported me during my school career. Lastly, I dedicate this work to myself for the hard work.

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CHAPTER 1

INTRODUCTION

Purpose of the Study

This research aims to identify and quantify critical areas for hazard minimization and identification in construction operations using 3D BIM Visualization and VR devices. BIM is the process of creating and managing the data for a created asset throughout its existence, from planning and design through construction and operations. The VR is an artificial environment created using software and presented to the user in a way that makes them overlook reality and assume it is genuinely real. In the construction phase, BIM has enabled the construction professionals in identifying, visualizing, and mitigating risk before problematic conditions occur. As a result, the demand for BIM applications to improve a safer protection approach from public and private owners in the construction industry has also aided rapid adoption. Via experiments and questionnaires with construction professionals, the researchers will go over a set of visual representations for construction activities and detect potential hazards. The analysis employs a mixed methodology (quantitative and qualitative) and an empirical case-study approach. The researchers believe that integrating advanced information technologies such as 3D BIM and VR, Augmented Reality (AR), and Mixed Reality (MR) can significantly improve the safety practices in the construction execution zone and simultaneously reduce the number of incidents or fatalities to create a safer workplace in this industry.

Research Background

Construction hazards are a worldwide issue. According to the United States Bureau of Labor Statistics, in 2020, 1008 fatal occupational injuries occurred in the construction industry

(BLS, 2020). According to these figures, construction safety is still a significant issue in the construction industry. Inexperienced engineers or managers, inadequate safety training and procedures, a lack of safety control, inspection, and proper implementation of safety guidelines are all factors that contribute to deadly incidents in the construction industry. Most importantly, a significant number of hazards in the construction industry are not recognized by construction professionals. Albert et al. quantified that construction professionals could not identify in the typical workplace on average “more than 50%” of the construction-related hazards (Albert et al., 2014). Several studies on construction safety have been conducted over the years to approach and define the safety hazards using different techniques, tools, and, more recently, virtual applications. However, severe, or fatal accidents in the building industry continue to be a significant hindrance. Alsharef et al. mention that “unrecognized and unmanaged” construction hazards could increase the potential of injuries occurring as workers do not feel safe or engage in “risk-taking behavior” in the presence of the construction hazards (Alsharef et al., 2020). After all, many construction safety innovations have been invented and implemented to prevent and reduce safety accidents in the construction industry. With the introduction of 3D BIM, VR, MR, and AR devices, there has been a noticeable trend of using sophisticated immersive applications to create an artificial environment for visualizing complex workplace situations, acquiring risk-preventive knowledge, undergoing virtual training (Li et al., 2017) and most importantly, identifying and eliminating potential construction hazards to prevent from any accidents.

Aside from this, BIM aids in identifying hazards and responding quickly to them to avoid construction incidents and forecasting, planning, and monitoring the schedule. Over 40% of professionals from all three sectors of the Architecture, Engineering, and Construction (AEC) industry indicated BIM was important during the design development and construction documentation phases (McGraw Hill Construction, 2012). BIM has significantly influenced the AEC industry over the last decade as one of the most widely used information and communication technologies. Also, construction professionals have increasingly used VR technology to train employees with simulations of safety hazards. Eiris et al. mention that "with the use of these digital replications of reality utilized computer-modeled environments to provide a medium to visualize and interact with hazardous conditions while enhancing safety knowledge rendition and increasing engagement in the learning process" (Eiris et al., 2020). Implementing these modern tools and technologies in the construction industry in any activity tends to comply with occupational safety and health regulations. For example, in the United States, "The Occupational Safety and Health Administration (OSHA) requires employers to instruct each employee in the recognition and avoidance of unsafe conditions" (Hinze, 2006).

Traditional training programs, such as computer-based learning, cannot deal with various situations and circumstances in identifying or minimizing the appearance of safety hazards. Furthermore, on-the-job preparation is not feasible for projects that place a high priority on quality because on-site work conditions are rarely disclosed before the actual project starts. As a result, VR has been promoted to address some of these issues in the current industry. New technologies have enabled real-world platforms and training to potentially identify hazardous conditions or environments before and during construction execution. The virtual environment effects can be used and played in real-time using hand tools such as picking and pulling. Because of their potential to significantly increase efficiency, safety of construction professionals, and hazard identification in the virtual environment, VR technologies have been quickly adopted in the construction industry. For the past two decades, various visualization techniques, such as BIM, VR, AR, and MR have been implemented to enhance virtual learning experiences, whether in the immersive virtual environment during the pre-design or at the actual construction work zone, to better acknowledge safety procedures in the construction industry.

In recent years, the construction industry has seen a significant increase in the utilization of technologies such as BIM, VR, AR, MR, and other Head Mounted Devices (HMD) at various stages of the project cycle. Because of the rapid advances in technology used in the construction industry, delivering adequate safety training programs in an immersive simulated environment and on a real construction site using VR, AR, and MR devices has helped enhance workers' everyday practices in identifying safety hazards. According to Azhar, modern technologies such as BIM, and 3D immersive reality environments, for example, VR headsets (like HTC VIVE Pro, Oculus, etc.), have improved construction safety allowing “architects, engineers, and contractors to visually access the job site conditions and recognize possible hazards before the construction proceeds” (Azhar, 2017). However, Toan et al. mention that the critical challenges in construction safety management include inadequate safety training, inadequate and incomplete work planning and supervision, and a lack of timely information exchange about safety. A variety of research on enhancing safety through construction safety management employing BIM is currently being conducted. Their methodology enables the visual assessment of workplace conditions as well as the detection of dangers (Toan et al., 2021). Besides VR, AR can also visualize the 3D model in the immersive environment. AR uses sensory technology to hear, feel, and view physical models with augmented virtual information in an immersive environment. Dangerous items can be reflected in the virtual world with these devices, reducing the construction activity's risk of harm or injuries.

These technologies may also provide construction workers with safety information through cell phones and other communication devices, effectively raising awareness. In this research, a total of 107 journal papers were thoroughly examined. A research topic and activity classification table are created from the journal papers found, including the journal publisher, journal title, authors, date of publication, activity type, research technique, and hazard types. This table also includes the usage of VR, AR, and MR devices and various BIM technologies (like Revit, AutoCAD, Civil 3D, Bentley) to identify and regulate construction safety concerns in certain journal publications. Several keywords were entered to search for and find related articles, such as virtual reality, augmented reality, mixed reality, building information modeling, safety hazards, and the construction industry, were entered to search for and find related articles. Based on the findings from the literature review, the current research shows that BIM embedded with VR, AR, and MR devices for safety training effectively identifies hazards in the construction industry.

Problem Statement

The research problem of this study was addressing safety hazards occurring in the processes of construction projects' execution. For many decades construction hazards have been an issue in the industry, many construction workers have been seriously injured, and many fatalities have occurred during project execution. Accidents in the construction industry are caused by inexperienced engineers or managers, insufficient safety training and procedures, or a lack of proper safety management, inspection, and correct safety norms. Most critically, many construction-related hazards are not always recognized by construction professionals. According to Albert et al., construction professionals could not identify "more than half" of the construction-related dangers in the typical workplace (Albert et al., 2014). Over the years, several construction safety studies have been undertaken to approach and establish safety regulations utilizing various methodologies, processes, and, more recently, virtual applications. However, severe, or deadly accidents in the construction sector continue to be a significant impediment.

On the other hand, many construction safety improvements have been developed and implemented to avoid and decrease construction-related accidents. With the introduction of 3D BIM, VR, MR, and AR for safety training in the immersive virtual environments, the trend towards highly developed immersive applications can be seen to create an artificial environment for the visualization of places for complex work. According to Li, et al., adequate risk prevention knowledge and safety training courses may help to identify or eliminate possible construction hazards and to avoid any accidents (Li et al., 2017).

Only four main construction activities were chosen for the case studies in this study. These four activities were chosen from a total of six states, including Georgia. The hazardous scenarios were created using actual data from different construction companies as well as a database of OSHA jobsite hazards downloaded from the OSHA website. BIM, VR, AR, and MR are all included in the literature review. This study covers only the basics of AR and MR and how these devices can be used to identify construction-related activities. However, the case studies were tested using only 3D BIM models and the VR HMD in this study.

Hypothesis

- Alternative Hypothesis (H_a): Implementing BIM and VR together in construction projects would lead to safety hazard identification and minimization in the construction process.
- Null Hypothesis (H_o): Implementing BIM and VR together in construction projects does not affect safety hazard identification and minimization in the construction process.

To test the hypothesis, the square test was used to examine the variability of hazard recognition and minimization of the independent variables (i.e., demographic questions) crossed with the dependent variables (i.e., safety training, use of technology, and the overall perceived safety performance). Multiple chi-square tests were performed among dependent and independent variables to find evidence of significance. The observed values are those values which the researchers collected from the survey and the expected values are the expected frequencies based on the null hypothesis. These values are used to calculate the value X^2. The authors expected a significant reduction in identifying hazardous situations during the project execution.

$$X_c^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

where, X^2 = chi squared

- O_i = observed value
- E_i = expected value

Research Limitations

With the 3D BIM and VR technologies, the study could find more hazards in the pre-construction design and reduce the number of hazardous activities during the actual construction execution. However, the case study data was developed from the construction activities analyzing the data only in Georgia and five other surrounding states. Also, only four different construction activities were selected for a case study. However, the case study approach and surveying local/regional industry have certain drawbacks in terms of providing adequate data to conclude more generally. As a result, future research may be conducted in various geographical locations and, with various construction-related operations, using similar or different research methods in order to predict a better hazard identification which may minimally impact performance for those operations. Future recommendations for this or similar research areas may include the followings:

- Research needed in wider geographical areas
- Collect a larger sample population for the surveys
- Research in multiple construction activities must be performed
  - Large commercial projects
  - Residential only, industrial, etc.
- VR devices for in-field testing with actual trade practitioners (including AR, MR)

CHAPTER 2

LITERATURE REVIEW

Jobsite hazards in the construction industry have been a serious issue worldwide. According to OSHA, out of 4,779 worker fatalities in the private industry in the United States in the calendar year 2018, 1008 (or 21.1%) were in construction, making one in every five worker deaths (OSHA, 2018). These OSHA statistics proved that safety remains a serious problem in the construction industry. The company safety standards and the OSHA regulations play an essential role in improving safety hazards at the construction site. The engineers should understand the importance of safety hazard recognition and the essential considerations when preparing the construction plan and the specifications before the actual construction (Gambatese et al., 2015).

Despite this, the construction industry has one of the highest accident rates of any industry in the world (Wu and Fang, 2012). Maintaining a healthy environment on construction job sites, on the other hand, is a persistent problem for the construction industry (Webb and Langar, 2019). According to Hinze and Holt, creating a safer construction zone requires extreme effort, including owners, designers, construction companies, construction professionals, safety regulators, and educators (Hinze, 1997 and Holt, 2001). Despite significant advances in construction technology and processes in recent years, the construction industry's safety record remains one of the worst of all industries worldwide (Huang and Hinze, 2006). The traditional method of safety hazard identification was focused on relevant sources from the 2D drawings, past accident cases, and other similar knowledge from the construction workers was used to prevent safety measures against unknown safety hazards through project meetings among the construction professionals (Bahn, 2013). The proper execution of safety protocols within the construction professionals in terms of "sensing, assessing, and removing possible hazards" depends entirely on hazard detection (Sacks et al., 2015). However, it is difficult to approach the construction participants' precautions and implement them in actual construction in uncertain circumstances (Albert et al., 2014). Various technologies and systems, such as web-based technologies, cloud computing, BIM, VR, and tracking technologies, have been introduced in the construction industry over the last decade to enhance project communication, collaboration, preparation, and monitoring. These technologies and systems directly contribute to the detection, management, and minimization of construction safety hazards (Lbem and Laryea, 2014 and Adwan and Soufi, 2016).

In recent years, modeling and simulation in VR and AR environments to train construction workers for safety hazard detection and minimization have appeared to improve the "immersive and interactive experience" (Perlman et al., 2014 and Hadikusumo and Rowlinson, 2002). One of the essential technologies implemented in the modern construction industry is BIM. BIM implementation in the construction sector has been rapidly increasing due to its effective results. BIM is defined as "a cohesive group of building components with digital representations that contain data attributes identified in software applications and parametric rules which can be manipulated" (Eastman et al., 2011). Using these modern technologies, BIM applications such as Autodesk Revit, CAD 3D/4D, Navisworks, and Bentley systems have helped control safety hazards with the predesign. There has been much interest in using BIM to improve worksite protection by safer design and work systems over the last decade (Azhar and Behringer, 2013 and Chi et al., 2012). Construction professionals may use BIM to envision worksite environments and recognize possible hazards. BIM aids in identifying hazards and responding rapidly to them to avoid construction-related incidents and forecasting, preparing, and monitoring the safer work zone in the construction industry (Martinez et al., 2017). Furthermore, BIM offers a powerful forum for creating and applying "prevention by design" principles, assisting with engineering and administrative protection planning and control tasks during the design and construction phases (Zhang et al., 2013). However, most construction industry accidents are attributed to poor job preparation and supervision, inadequate coordination between staff and managers, and a lack of safety training and practices (Lappalainen et al., 2007).

VR, AR, and MR platforms, in addition to BIM, have been successfully applied in various industries, including AEC (Wang and Dunston, 2007 and Jeelani et al., 2017). Users can quickly and repeatedly encounter hazardous construction situations that were previously impossible, risky, complicated, or costly to experience using these technologies (Eris et al., 2019). Pedro, et al., proposed the framework that provides interactive, accessible, and captivating learning environments for learners to acquire safety knowledge and develop hazard detection abilities in the construction industry through VR, MR, AR, and other related mobile devices and applications (Pedro et al., 2016). Multiple layers of information, such as BIM, real-time geographical location, and audio warnings, are integrated into VR and MR to create information-rich experiences for creative construction safety initiatives (Moore and Gheisari, 2019). As a consequence, the use of these technologies can result in advanced occupational safety protection by connecting the safety issues more extraordinary, providing extra illustrative site layout and security plans, providing methods for dealing with and visualizing plans and site frame data, and providing updated safety communication in various situations on the worksites Li, et al., 2018).

VR and MR technologies are being used to help transition information to staff, effectively alert them of site hazards, and eradicate hazards both before and during construction (Moore and Gheisari, 2019). Health and safety professionals on construction sites may use 3D renderings created by BIM models and understand these animations to identify safety procedures ahead of time (Azhar, 2017). This study's importance lies in the fact that it presents the current state of VR and MR in enhancing construction safety, thus drawing more attention to these promising technologies and, as a result, improving construction safety (Moore and Gheisari, 2019). To this end, information visualization technologies such as BIM, VR, AR, and other game-based technology have been used to advance existing safety management and safety hazard recognition practices in the construction industry (Chi et al., 2013, Guo et al., 2012, Li et al., 2012, and Li et al., 2017).

A comprehensive literature review was conducted herein through the distinguished relevant sources; journals, books, blogs, websites, conference papers, and review papers from 1995 to 2021. A total of 107 journal papers related to BIM, VR, AR, MR, and safety in the construction industry were read carefully and extracted. These relevant journal papers were discovered from Google Scholar, Science Direct, the American Society of Civil Engineers (ASCE) journals, and many other publishing avenues. The below pie chart shows the actual percentage distribution of journal papers used from different sources. Figure 1 shows the number of different journal and conference papers used to extract information from other researchers' recent advances in BIM, VR, AR, and MR to approach and identify safety hazards in the construction industry.

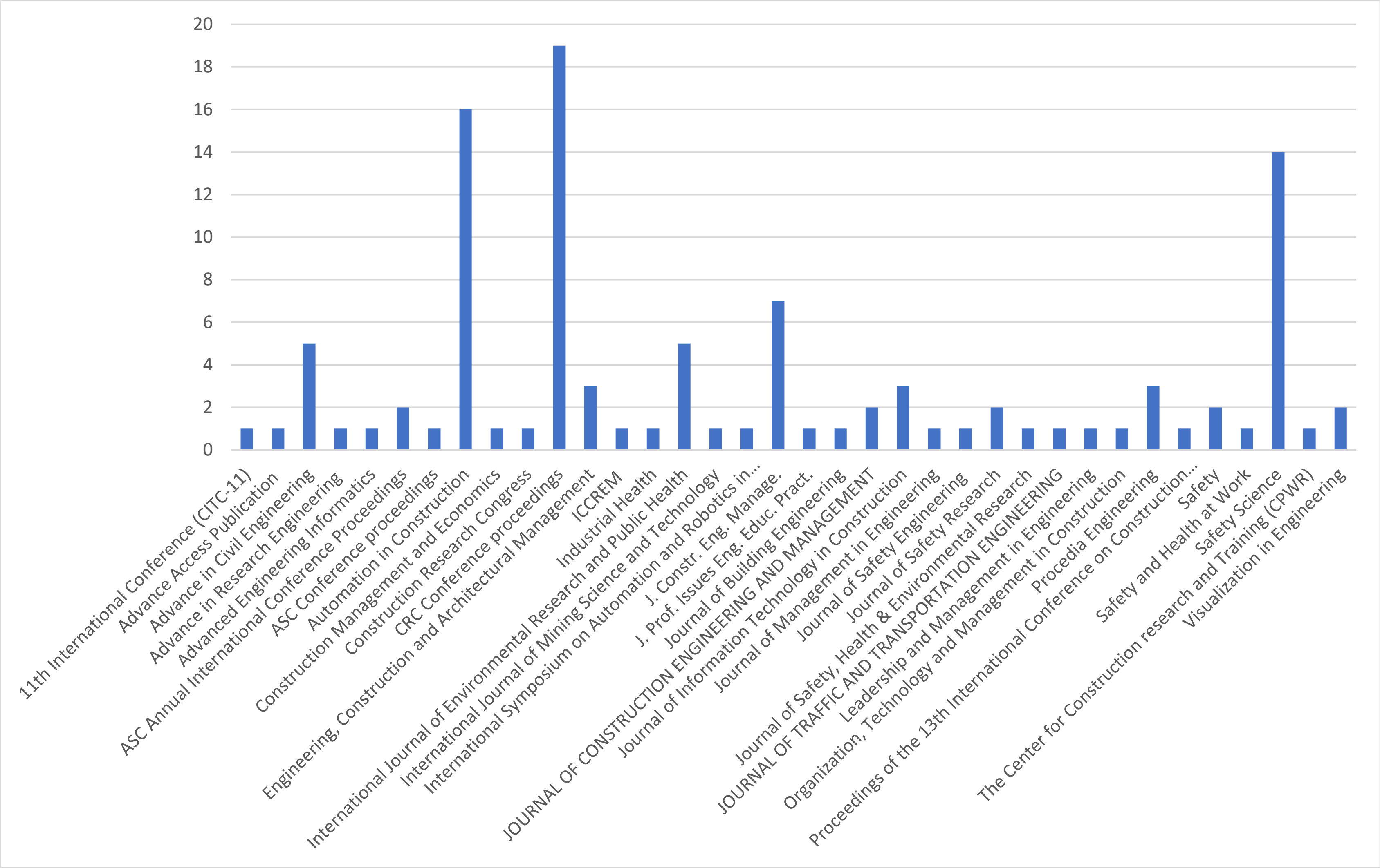


Figure 1: Journals classified on the number of manuscripts

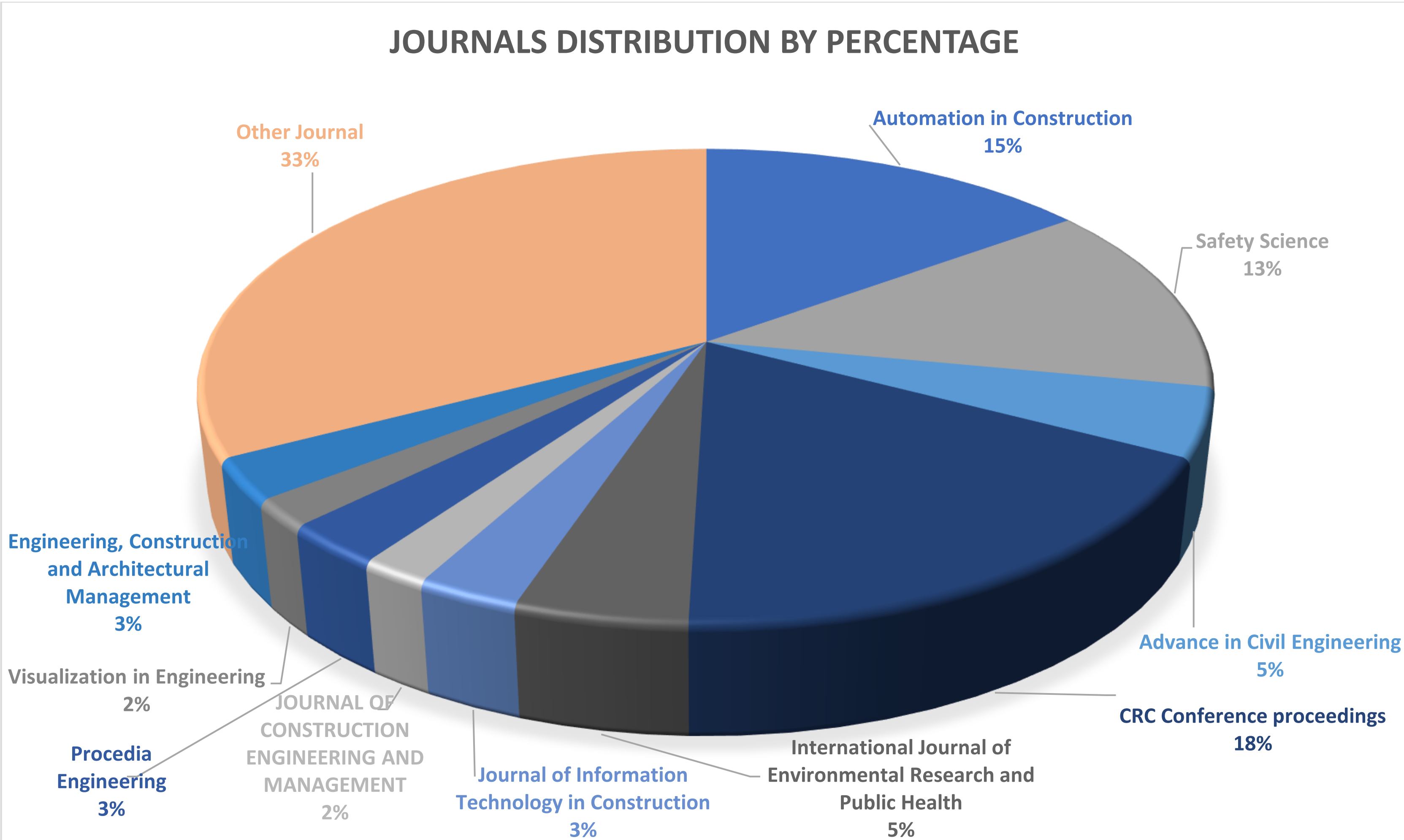


Figure 2: Percentage (%) distribution of the Journals used in this literature review

Figure 1 displays a bar chart representing the number of journal papers used in this review from various publishing journals. Virtual Design and Construction (VDC) technologies and their applications for construction safety were reviewed in this study. BIM, VR, AR, and MR were examined among the VDC technologies. As the construction sector has experienced technology interference into traditional workflows, this study analyzed research work from 1995 to 2021. A total of 107 research publications were examined in this in-depth evaluation. This comprehensive technological intervention assessment examined existing technology adoption obstacles for enhancing construction-safety scenarios and relevant issues for future study. Table 1 represents the Journals that were used. Out of them, Automation in Construction, Safety Science, Safety, CRC Conference proceedings, and many other Journal papers were analyzed and then I identified the research gaps that needed to be addressed. Figure 2 shows the percentage of the journal paper used in this review. About 15% of the papers are in Automation in Construction, and 13% in Safety Science.

Table 1: Journal papers used in this literature review

Journal Title	**Abbreviated Journal Title**	**Number of relevant papers**
Advance in Civil Engineering	ACE	5
Automation in Construction	AC	16
CRC Conference proceedings	CRC	19
Engineering, Construction and Architectural Management	ECA	3
International Journal of Environmental Research and Public Health	IJERPH	5
Journal of Construction Engineering and Management	JCEM	2
Journal of Information Technology in Construction	JITC	3
Procedia Engineering	PE	3
Safety Science	SC	14
Visualization in Engineering	VE	2
Other Journals	OJ	35
Total Journals		**107**

Building Information Modeling (BIM) for Construction Safety

The National Institute of Building Sciences (NIBS) has defined BIM as a "digital representation of physical and functional characteristics of a facility that serves as a shared knowledge source for information about a facility" (NIBS, 2019). Furthermore, according to Meža et al., BIM is a building design approach in which a high-level standardized digital model is generated rather than details about a building being spread through various drawings, tables, papers, and documents (Meža et al., 2014). BIM in a project reduces risks by reducing errors in plans and communication between architects, engineers, project managers, and fosters productivity in coordination and information sharing among these professionals to ensure accuracy and reliability. In the AEC industry, BIM is used for 3D visualization, cost estimation, 4D models, clash detection, hazard identification, feasibility analysis, construction examination, and many other uses. By identifying, visualizing, and mitigating risk before problematic conditions occur in the project, BIM has allowed for identifying safety hazards in the construction phase. As a result, the demand for BIM adaptation from both the public and private construction sectors has fueled these rapid implementation rates among design and construction firms worldwide. Since the last decades, BIM uses in the building industry to address safety hazards have increased dramatically. BIM was used by 70% of architects, 67% of engineers, and 74% of contractors in 2012 (McGraw Hill Construction, 2012). However, in recent years, the usage of BIM has increased during more recent years. BIM can be used to gather information about the physical project, preparation and coordination sequencing, workflow, logistics, safety hazards identification by allowing teams to perform pre-construction risk assessments and make regular changes to safety plans and thus avoid hazards (Webb and Langar, 2019).

BIM in construction projects reduce risks by minimizing errors in plans and communication between architects, engineers, and project managers and fostering productivity in coordination and sharing information among these professionals to ensure reliability and accuracy. Zhang et al., mentions that the increasing use of BIM in the AEC industry changes how safety is approached (Zhang et al., 2013). A growing number of AEC firms use BIM to manage project information and support information sharing among stakeholders (Goedert and Meadati, 2008). It is increasingly becoming an indispensable information platform for identifying safety hazards and making construction decisions (Chen et al., 2015). BIM implementation lowers risk by increasing performance, reducing errors or misinterpretations between designers, engineers, and contractors, and requiring cooperation and information sharing among all parties involved to ensure accuracy and reliability (Cefrio, 2011).

The implementation of BIM in the AEC industry is changing how safety hazards can be approached. Several studies show that BIM can help the AEC industry recognize safety hazards, clash identification, construction progress monitoring, scheduling, design continuity and visualization, data integration, lean construction implementation, or enhanced team member coordination (Martínez, 2017). According to Azhar, the research on the use of BIM technologies in safety planning and management was for design for safety, design inspection and control, safety planning, safety training, facility management, and emergency response (Azhar, 2017). Due to the vast amount of data generated in schedules, records, and photo logs, tracking the implementation of every single component of a building, and representing it on BIM models can become highly labor-intensive and error-prone in large-scale construction projects (Rahimian et al., 2020). BIM can be used for employee orientation and worker safety training, site hazard detection, excavation hazards, site traffic coordination, and other installation/operations after a project is completed

(Rajendran and Clarke, 2011). Traditional educational systems, such as computer-based learning, struggle to prepare decision-makers for various scenarios. Furthermore, on-the-job preparation is not feasible for projects that put a high priority on quality because on-site work conditions are rarely disclosed before the project starts. As a result, BIM has been promoted to fix these practical issues in the construction industry.

Virtual Reality (VR) in the Construction Industry

VR is defined as a computer-generated depiction of spatial data that may be interactively controlled by a user and presented on any sort of screen. Furthermore, real-time architectural walkthroughs, where users can explore and travel through interiors, have been suggested as a critical application (Mobach, 2008 and Liu et al., 2014). VR combines digital image processing, computer graphics, multimedia technology, sensor technology, and other knowledge built throughout computer technology advancement. This tool allows users to communicate with simulated environments by grabbing and dragging objects and simulating the user for heights, slab hole opening, drywall installation, steel framing, or any other construction-related work to recognize potential safety-related hazards before the actual construction. “Virtual Reality is powerful in its ability to generate unlimited training abilities” (Wang and Dunston, 2007). VR innovations have been quickly adopted in the construction industry because they improve design efficiency, construction health and safety, and equipment training. The effects can be seen and interacted with in real-time using hand tools such as picking and pulling in the immersive Virtual Environment. The rapid changes in the construction industry's technology have made appropriate safety training programs to enhance construction workers' everyday activities by recognizing safety hazards increasingly necessary. For that reason, the implementation of VR technology has been rapidly increasing in the construction industry.

VR devices allow the user to fully immerse themselves with the integration of a 3D BIM model, which can be manipulated and provide a real sense of physical presence in a virtual environment. The 3D model is rendered in the virtual environment, and therefore VR offers more realistic possibilities for construction professionals to explore and experience the safety hazards during the design phase. To achieve this, three-dimensional (3D) modeling is integrated with virtual reality devices such as HTC Vive Pro to generate immersive reality, initially through head mounted devices such as handles, helmets, and gloves, through the computer and an internet connection. VR on 3D modeling technology, on the other hand, uses geometric design to complete the construction design approach that creates more realistic performance scenes and artifacts in the real world, as well as build animations in the immersive environment, typically with the aid of a professional modeling programs like Unity, 3M, Maya, and others. Since VR technologies allow users to simulate and imagine models in an interactive virtual environment, the use of this technology in the AEC industry has increased for various reasons. VR allows one to explore together in a virtual space, a place that does not occur physically when participants are in different geographical locations within the AEC industry (Asgari and Rahimian, 2017). According to Getuli et al., as the use of BIM and the availability of 3D models grows, VR technologies allow users to simulate in an immersive virtual environment easily and understand "basic design communication and validation" (Getuli et al., 2020). Moore et al. define pre-construction safety preparation as "a significant preliminary step that can be taken to avoid unsafe construction situations by careful design before the project begins" (Moore et al., 2019). Due to the immersive 3D presentation capabilities of 2D displays, the Virtual Environment (VE) provides unique opportunities for users to encounter real-time interactive objects and environments (Asgari and Rahimian, 2017).

Construction is a high-hazard industry, so estimating and preventing hazards in the design's execution is an important goal of VR tools (Asgari and Rahimian, 2017). Additionally, the ability to estimate and prevent hazards in the design's execution is a fundamental goal of VR tools (Asgari and Rahimian, 2017). Therefore, VR technology enhances coordination for key players in the construction industry, thanks to excellent concept visualization and a better understanding of the project (Jiao et al., 2013). VR allows users to completely immerse themselves in a 1:1 scale, manipulable 3D BIM model, giving them an accurate sense of presence in a room that has yet to be built (Poussard et al., 2014). In addition, different VR applications have been introduced to assist designers, developers, and architects, including Samsung Gear VR, Oculus, CAVE, HTC Vive. Many sensing devices, such as Myo, Leap Motion Controller, Nimble VR, and PrioVR related to Virtual Reality, have been built with the primary aim of lowering prices, minimizing risks, and enhancing product quality (Asgari and Rahimian, 2017). Samsung Gear VR is a virtual reality system that allows users to experience the virtual world at a construction site or during meetings (Sampaio, 2018). However, a BIM model is needed to achieve a virtual environment using Gear VR for facility management purposes, as construction site pictures track construction phases (Gear VR, 2017). Indeed, BIM applications, such as Revit for visualizing and 3ds Max for rendering, should be familiar to the users. Also, the use of game engines like Unity3D with android studio is required to navigate within and outside the BIM model in a virtual world, and equipment for panoramic images and editing softwares that will help convert those photos to the 3D world will be required as well (Rho and Kim, 2015).

Practitioners and construction professionals are gradually turning to VR technology to provide training that simulates safety hazards. These modern virtual platforms use computer-modeled environments to provide a forum for visualizing and interacting with dangerous situations, improving safety experience retention, and increasing learning interaction (Eiris et al., 2020). From reviewing design choices and showcasing plans to designing out errors and ironing out construction and serviceability problems before breaking ground on-site, VR will play an essential role at all stages of the design-to-construction phase (Sampaio, 2018). Additional technology capacities concerning model-data retrieval are needed when bringing BIM data into a VR environment (Sampaio, 2018). Fully interactive VR software has extremely high-performance demands during a visualization, but additional technology capacities concerning model-data retrieval are required when bringing BIM data into a VR environment.

In fact, over the last decade, researchers have suggested several ways to use model-based VR for safety training in geometrically modeled environments like BIM. Materials, lighting, furniture, and other small details that make the VR experience feel real are added once the model is produced with a BIM tool like Revit inside the VR system. For instance, HTC VIVE is a virtual reality headset with an authentic experience. The HTC VIVE tracks and maps your movement around the room using two sensors in each corner of the room. The controllers are wireless, and the headset is connected to the computer via a lengthy cord. It is also necessary to have a computer with the high-processing power to run a virtual reality environment, which can be costly. SteamVR, a virtual reality game program, is used to power the Vive. Revit 2021 is used to create a 3D model of the building, then plugged into the device to determine potential risks. One can walk and view the model when projected in the HTC headset. As a result, construction hazards can be reduced by eliminating most of them at the pre-design process; this is a once-in-a-lifetime opportunity for any construction professionals on the job site and the construction industry.

The experience is like a walkthrough, but BIM includes data, and exploring BIM data when walking within a virtual model is convenient. For example, according to OSHA, today's VR immersive environment allows construction professionals to practice at heights without doing any physical work, which is one of the most vulnerable areas to construction hazards. This training helps construction professionals gain experience at such heights and gain comfort standing and working in such environments (Bosché et al., 2015). As a result, practical, immersive training could save the lives of construction workers who work at heights. In addition, Perlman et al., mentions that several studies show that introducing VR technologies to safety hazard detection and risk perception in the VR environment relevant to the construction industry increases "understanding and enable awareness" to the construction professionals (Perlman et al., 2014).

Augmented Reality (AR) in the Construction Industry

Augmented Reality is a "specialization of Mixed Reality, where the virtual objects are superimposed upon the real world, whereas in VR the user is completely immersed in a virtual environment" (Azuma, 1997). AR is a simulation technology that enables users to view virtual models in real-time in real-world environments, with construction being one of the most promising applications. AR superimposes artificial elements such as 3D models, interactive content, or text details on real-world images, expanding the user's interaction possibilities (Hsieh and Lin, 2011). Photorealistic augmented simulation of architectural plans, smartphone access, and input to digital building data during and after construction, enhanced connectivity, better safety hazards approach, and increased flexibility with BIM use are some of the advantages of Augmented Reality that users can expect. As a result, the incorporation of augmented reality as a new user interface allows for a radically new approach to the Design of a construction site layout (Wang and Dunston, 2007). On the other hand, AR does not involve creating a realistic illusion and can be thought of as an extension of VR, which incorporates real-world vision with virtual elements to construct a real-time mixed reality.

In comparison to a VR environment, Fonseca et al. found that AR allows users to interact with objects by changing their size, location, and other properties to make them fit seamlessly into the real World (Fonseca et al., 2014). The dangerous object can be reflected in the simulated environment using Virtual Reality technology, significantly minimizing the risk of being subjected to any incidents. These technologies also provide construction workers with safety information via mobile devices, effectively increasing awareness. Clevenger et al. created a BIM-enabled virtual construction safety training module to determine the importance of 3D visualization in construction safety training and education. Clevenger et al. found that BIM-enabled safety training is very successful in the construction industry (Clevenger et al., 2015). Furthermore, AR is the most ambitious expression of ambient intelligence (Riva, 2003), as it is an extension of the conventional virtual reality world. AR technology works by integrating appropriate digital knowledge into real-world environments to improve human understanding of real-world entities (Wang and Dunston, 2007). Furthermore, AR creates an atmosphere in which computer interfaces blend seamlessly into life, allowing users to communicate with other people or the environment most naturally and intuitively possible (Riva, 2003). When virtual objects, texts, or videos are superimposed over a real-world scene, augmented reality is known. Data, computation, and presentation are the three central AR systems components (Meža et al., 2014). Users may design and decide the construction worksite's layout by moving and placing these objects interactively

(Wang and Dunston, 2007). A sophisticated and detailed BIM model, which contains all the necessary information and the 3D geometry of all the facility's objects, may be used as a database combined with an AR approach to provide facility managers with an ambient intelligent environment (Gheisari, 2013). Since AR planner allows the construction worksite planner to position construction materials and equipment, handling devices, and the corresponding routing lines in the planned worksite, the proposed AR platform shortens and enhances construction worksite planning efficiency. Furthermore, the augmented reality interface enables users to immerse themselves in a new reality augmented with computer-generated content, thanks to the creation of advanced, lightweight, and inexpensive interaction and display devices (Wang and Dunston, 2007). The drawback of augmented reality is that it does not correspond to the real environment, making interaction with the natural world impossible. The user interacts in real-time with the digital environment, which comprises the physical and virtual worlds. It establishes a link between the virtual and actual worlds.

Figure 3: AR-based wearable glass for construction safety (Ahmed, S., 2019)

In Figure 3, soil excavation work is performed at the construction site. This activity is observed by the construction professional using the Augmented Reality device. This device allows users to identify the potential hazards during this work and warn if any unknown hazard is about to occur; for instance, one of the most common incidents during this work may be hit by an excavator. When the construction professional wears the AR headset, the range of safety zone can be viewed in the virtual environment. The green portion in the figure is an unsafe area to walk in when the excavator is working. Therefore, it is very unsafe for construction professionals to stand closer to this activity. Also, AR devices can help workers visualize the unsafe area and thus, minimize hazardous entering areas on the respective job sites by providing a better situational awareness.

Mixed Reality (MR) in the Construction Industry

A new environment in which a computer-generated virtual world coexists with the real world is known as mixed reality. MR, also known as hybrid Reality, combines virtual and augmented reality benefits. VR is a technology that replaces the real world with a virtual item to create an artificial environment. AR is a technology that outperforms the virtual world. It does not entirely replace the real world, but it adds a film of digital information and pictures. Mixed Reality is a continuum in which computer-generated content can be combined in various proportions with a person's view of a real-world scene, and it opens new possibilities for project life cycle experiences with virtual design knowledge and project partners. Milgram and Kishino note that the most transparent way to view a MR environment is one in which real-world and virtual-world objects are viewed together within a single display. (Milgram and Kishino, 1994).

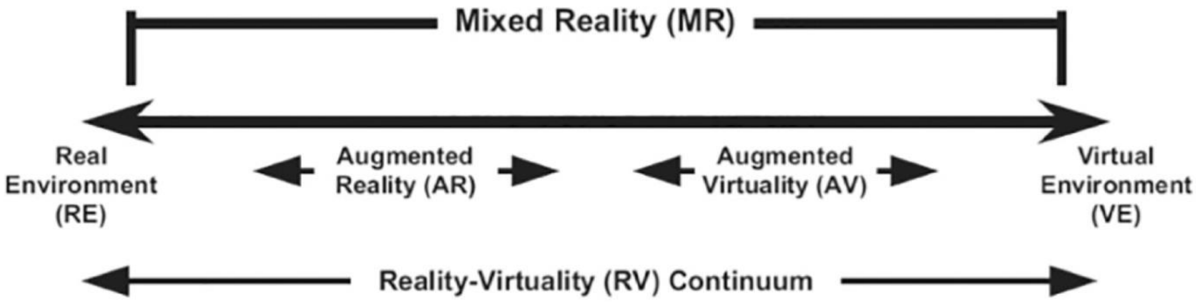


Figure 4: The Milgram's Mixed-Reality Spectrum (Li et al., 2018)

Figure 4 illustrates Milgram's MR spectrum, and the blue area represents the span of different MR classifications, which is a combination of RE, AR, AV, and VE. According to Milgram et al., "the most straightforward way to view a Mixed Reality Environment is one in which real-world and virtual-world objects are presented together within a single display, that is, anywhere between the extremes of the virtuality continuum" (Milgram and Kishino, 1994). Microsoft unveiled HoloLens to the world for the first time in 2016. It is a portable computer that can overlay holograms in the actual environment without any additional hardware. The Microsoft HoloLens, a mixed reality device, projects virtual 3D objects right in front of the user's eyes, allowing them to see how the virtual object interacts with the real world in real-time. HoloLens is a self-contained computer that runs the Microsoft Mixed Reality platform on Windows 10. It uses Wi-Fi and Bluetooth to communicate with other devices. The HoloLens allows users to visualize digital objects in the actual environment, distinguishing it from virtual reality (Figure 5).

Figure 5: Microsoft HoloLens 1 (Source: Microsoft)

Later, HoloLens 2 was released, an upgraded version of the original HoloLens. It was first released in February 2019. It can detect the user, track the eye, and project Holograms more naturally and comfortably. The user can engage with the Holograms more naturally by touching, gripping, and moving. The HoloLens 2 offers a larger field of vision than its predecessor. Even in a noisy environment, it can execute voice instruction. The headset can be worn for more extended periods and comfort than HoloLens 1. The HoloLens 2's display can be turned upside down, allowing users to use it whenever needed.

Overall, MR systems can be customized to increase knowledge usability for decision-making in concept analysis, job preparation, work execution and control, and safety inspection in the construction industry by strategically combining real and virtual data and employing intuitive human-computer interface devices. Since job site preparation is an essential part of the construction industry, MR technology may assist construction workers by offering training about actual construction site conditions. MR applications have a broad potential for identifying safety hazards and minimizing their role in the construction industry. According to Bosché et al, the type and degree of interactivity provided by MR devices provide a richer and more practical user experience (Bosché et al., 2015). As a result, they have the unique opportunity to deliver immersive and interactive virtual training scenarios in the construction industry. One of the latest developments of MR devices is Microsoft HoloLens 2.

Indeed, the proposed framework develops interactive, open, and captivating learning experiences using virtual reality, mixed reality, augmented reality. Other mobile devices provide learners with an experimental opportunity to acquire safe knowledge and develop hazard recognition abilities in construction (Pedro et al., 2016). Delgado et al. mention that AR and VR are still developing technologies, with several difficulties to be addressed, including form factor, see-through quality, field of view, image quality, occlusion handling, and vision correction capabilities (Delgado et al., 2020). The MR device can be integrated with any other 3D sharing platform like Unity 3D to view construction-related designs or modeling. MR devices can provide high-quality renderings and user interaction with complex designs in the artificial environment. Furthermore, the MR device provides an excellent approach to broader applicability and scalability to various construction training scenarios, allowing versatility in identifying construction-related hazards in the immersive virtual world. As a result, it is concluded that MR will help the construction industry by enabling construction professionals to visually immerse themselves in a virtual environment when conducting safety training.

Safety hazard training using BIM and VR-AR-MR devices

Most construction companies provide safety training to construction professionals for safety-related hazards identification and prevention of incidents in the construction zones. However, besides safety training, construction professionals play an essential role in determining their safety behavior while working in the construction work zone. According to Alsharef et al., traditional safety training systems are not built based on an accurate understanding of why construction professionals struggle to recognize and control safety hazards in the industry (Alsharef et al., 2020). Furthermore, Sacks et al. mentions that, although construction firms take drastic measures in terms of planning a secure working site, providing training and personal protective equipment (PPE), and implementing safety laws, construction workers may still be reckless, placing them at risk of injury or even death (Sacks et al., 2013). However, according to Bahn and Namian et al., previous research has revealed that construction professionals ignore 50% of building-related hazards (Bahn, 2013 and Namian et al., 2016).

The traditional safety lecture video presentation is inefficient in encountering safety hazards in the construction industry (Burke, 2006 and Wilkins, 2011). Yeh et al. mention that traditional communication methods make construction professionals carry a construction drawing to the site and require plenty of effort to abstract the information needed for safety hazard recognition and identification (Yeh et al., 2012). However, as technology advances in the construction industry, several businesses have begun to use BIM in conjunction with VR, AR, and MR devices for safety training and hazard detection. According to Perlman et al., VR training has become more successful in improving trainee attention and concentration (Perlman et al. 2014). For years, various virtual reality devices such as Microsoft HoloLens, HTC VIVE, Oculus Rift, Lenovo ThinkReality, HP Reverb, and others have been used. These devices have proven to be a helpful tool for viewing 3D models in interactive virtual environments. Cameras, sensors, microphones, and a small screen facing the eye are all mounted on the head to a HMD. The object in the immersive virtual world is moved using two controllers: left and right-hand controllers. Shu et al. discovered that using an HMD improved “user efficiency and understanding” of safety hazards compared to using a simulation on a computer screen (Shu, 2018). Modern 3D/4D technologies such as Revit, Civil AUTOCAD, Bentley have played a significant role in designing any construction activities before the construction. Most surprisingly, these technologies have been implemented together with reality devices for a better safety approach. The online 3D/4D model sharing platform such as BIM 360 has played an outstanding role in modern construction. With this application, any construction activity model can be viewed or modified, if necessary, from any part of the world. This application significantly impacted the industry, and therefore the use of paper-based construction models (2D) has been reduced to a minimum use. The hazard identification and the safety approach are most efficient in the 3D models rather than the 2D model representations. However, small construction companies still use the paper-based construction model representations to minimize operating costs.

When a construction model is depicted and employees can interact and collaborate on it, the efficiency of construction safety training will be considerably improved. Several researchers have used BIM as a critical tool, which has merged with VR technology, a game technology for safety instruction. BIM and VR have been merged to create a virtual building site to improve safety instruction. Integrating BIM with online gaming technology, where workers may carry out their activities using a computer connected to the Internet, improves the interoperability and collaboration of this training technique (Toan et al., 2021). Indeed, emerging digital technologies like BIM, VR, AR, and gaming can turn old document-based safety processes into digitized safety practices, allowing safety managers to realistically observe and analyze building sites to create proactive safety measures and practical safety training (Muneeb et al., 2021).

Identification of frequent unsafe hazards

Many unpredictable elements jeopardize construction safety, such as weather, staffing, and procurement-related concerns (Ji and Leite, 2015). Most events occur due to the unique nature of construction, human behavior, difficult working circumstances, and a lack of safety management (Koehn et al., 1995); for example, underground construction has numerous complexity that may threaten safety during construction (Li et al., 2018). Many accidents in the construction business are recurring (Kim et al., 2011). Human mistake is caused by a lack of skill in hazard recognition, which is one of the elements compromising safety (Mo et al., 2018). The construction industry's unpredictable and complicated nature necessitates the use of new technology to successfully cope with numerous catastrophes (Malekitabar et al., 2016). Various technology-driven applications, such as BIM and associated immersive technologies for the visualization and simulation of design and construction information can be used to resolve such issues. Where standard construction safety approaches fall short of eliminating dangers, the technologies can significantly enhance workers' hazard recognition, safety planning, and management skills, hence lowering the risk of on-site incidents.

By addressing the linguistic barriers in international construction projects, BIM enables more accessible communication and dissemination of information. Building information visualizations ensures that information is accessible to everyone, regardless of their position or ability to read or interpret language. In addition, BIM models can be used for various purposes, such as facilitating expert discussions on the construction process or hosting informational workshops for project stakeholders. This method may help make construction operations more understandable for those with no prior experience in the field. During safety meetings, 3D BIM can be utilized to aid safety professionals in detecting hazards. Studies were conducted to encode provisions of the law on labor safety and use BIM as a source to obtain information about structures, hazardous positions, and the construction schedule to identify hazards through an automated rule checking system to automate the hazard identification process.

Previously, only project-related information was considered during the hazard identification process. However, new studies have offered new information on building sites, warehouses, temporary housing, equipment, and other locations to help identify danger (Zhang et al., 2015 and Malekitabar et al., 2016). Safety hazard analysis approaches can be integrated into the 3D BIM model for risk and construction safety analysis. OSHA recommends Job Hazard Analysis (JHA) for construction operations to identify and respond to potential hazards. Work hazard analysis is a technique for predicting potential dangers by focusing on the job phases. Also, JHA is concerned with the interactions among workers, jobs, tools, and the working environment. Indeed, JHA will assist in identifying dangers and gradually eliminating or reducing hazards to a lower level.

Companies are now looking into novel ways to increase worker safety. Chen et al. mention that many incidents may be avoided if proper danger identification procedures were followed (Chen et al., 2013). In addition, immersive technology has been shown to help with hazard recognition (Tixier et al., 2013). Workers could benefit from pre-construction visualization training that allows them to experience real-life hazard scenarios before they begin building. Giving continuous feedback during training in a realistic construction setting could improve workers' hazard-determination abilities (Pereira et al., 2018). As a result, VDC technology can help to increase overall safety.

According to research, BIM and other visualization technologies have aided in identifying, assessing, and mitigating safety issues throughout the design phase (Malekitabar et al., 2016).

However, digitized safety management procedures are still lacking in the construction business. The impact of combined VDC and VR technology use on worksite safety management in construction activities and the consequent productivity is the subject of this study. Nonetheless, construction safety based on a 4D BIM model, rather than a 3D BIM model, could apply the safety plan in real-time and connect the safety plan with the construction plan. Tools and working practices must be improved to fulfill construction safety management with the help of BIM technology. Furthermore, more practical experience in safety planning is required for all safety and construction personnel.

Moving roofing materials for roofing work and installing solar panels or shingles on the roof, lifting roofing materials with mechanical devices, a worker not following OSHA guidelines (not properly fixing on anchors) while working on the roof or a worker not wearing PPE while performing roofing works, falls due to weather conditions while working on the roof, and finally hazards due to unbalanced ladders on the construction site are all case studies of roofing work hazards in this research. Hazards from excavators or tower cranes hitting power lines, getting caught in between electrical equipment, hazards from naked (energized) wires lying on the ground, installing transformer/HVAC units into the building or away from the building sites, and electrocution while installing electrical appliances into the building are all part of the electrical work. Hit by a falling material from a lifting tower, trapped between mechanical devices while conducting concrete work, pouring concrete into deep foundations (chemical burns), and being hit by a concrete truck or an Excavator into a tight construction site are all risks associated with concrete work. Finally, mechanical works include hazards such as being struck by an object while lifting with a mechanical device (such as tower cranes), loading, and unloading materials from a truck with a mechanical device (such as forklifts), being caught-in-between due to poor visibility by trucks, dozers, and excavators, and forklift hazards.

Benefits of Virtual Reality Safety Training

There are many benefits of safety training to construction professionals. Not everyone working at the site has been exposed to various construction hazards, and therefore, they might not be able to eliminate some of these hazards from occurring. For this reason, it is proposed to provide safety training to the construction workers in the virtual learning environment or at the actual construction site. This training allows users to interact with any possible construction hazards occurring at the face of actual construction and find ways to eliminate these hazards from occurring again. Virtual Reality Learning Environment (VRLE) is described by Mikropoulus and Nastis as "a virtual environment based on a specific pedagogical model, incorporates or implies one or more didactic objectives, provides users with experiences they would not otherwise be able to experience in the physical environment, and can support the attainment of specific learning outcomes" (Mikropoulus and Nastis, 2011). There are many benefits of virtual training, and therefore many lives potentially can be saved because of this practical construction safety training environment. Some of the expected benefits are described below. The information described below was extracted and it is cited from the web source 3M.com (3M, 2020).

1. Safe - Users can understand the nature of safety-related construction hazards during the safety training in an immersive virtual environment and, therefore, implement safety procedures in the actual construction to escape from any harmful activities.
2. Memorable – VR helps create an engaging experience that can be integrated into existing training programs to help capture worker's attention

3. Cost-Effective – VR training experiences can be delivered right at the construction site or at the training room, effectively saving cost.

4. Interactive – VR provides a fun and enjoyable way for construction professionals to practice skills and effortlessly reinforce knowledge about construction safety hazards.

5. Immersive – Construction professionals can simulate an immersive virtual environment to walk through and identify common construction hazards for accident prevention in the construction site.

Table 2 represents the many online platforms that may incorporate 3D models into a virtual environment. Oculus Quest 2 (HMD) was employed in the virtual laboratory as part of the research and testing of the 3D BIM models. On the other hand, this device offers an in-built framework for integrating 3D models along their descriptive situational construction objects (families). The below online platform acts as a bridge to connect 3D BIM models into the HMD. In this research, IRIS VR was used to integrate 3D BIM models into the Oculus Quest 2 HMD. Enscape and Invonto are other online platforms that are mostly used to integrate within the VR environment. While Trimble is feasible only with the MR environment such as Microsoft HoloLens 2.

Table 2: Lists of the online 3D integrating platforms to the Virtual Headsets

Online Platform	**Supported VR/AR/MR devices**
Trimble	Microsoft HoloLens
Iris VR	HTC VIVE, Oculus Rift, Oculus Quest, Windows MR
Modelo	HTC VIVE, Oculus Rift
Serious Labs	HTC VIVE, Oculus Rift
Enscape	HTC VIVE, Oculus Rift S
Unity 3D	HoloLens, HTC VIVE, Oculus
Invonto	HTC VIVE, Oculus Rift, Samsung Gear

As today's construction industry is evolving and infusing more technology, computer-based training is becoming more common to use. There are also various programs for detecting safety risks, such as the Virtual Reality Environment, System for Augmented Virtuality Environment (Albert et al., 2014). The company has built Cave Virtual Environments (CAVEs) (Perlman et al., 2014) and Visualized Safety Management Systems (VSMS) for the safety training (Park et al., 2013). Compared to 2D sketches or other related records, the hazards are often found in the immersive virtual world (Sacks et al., 2009). According to Li et al., an attempt has been made to "embed" virtual and augmented Reality for better knowledge and comprehension of construction safety hazards (Li et al., 2018). Construction workers use virtual reality training to learn the construction process and appreciate construction complexities to identify hazards before they arise on the actual construction site. However, a lack of adequate preparation contributes to the inability to identify dangerous behaviors, resulting in unsafe workplace activity and a detrimental impact on safety hazards. Correct information can be obtained, and safety hazards can be visualized in 3D or 4D models to prevent unsafe working environments. With proper and appropriate safety training and the implementations of VR and AR optimized BIM, accurate information can be obtained, and safety hazards can be visualized in 3D or 4D models to prevent dangerous working environments (Wang et al., 2014, Lakaemper et al., 2009, and Wang, et al., 2013).

As a result, workers can detect and track discrepancies between the hazardous site situation and the norm's safety regulations. The modern construction safety training in Table 3 has been referenced and listed below, with various techniques, definitions, hazard types, the technology used, and examples from multiple authors. (Alsharef et al., 2020). Various technologies including 3D BIM, MAYA, Unity, Revit. have been integrated with virtual, augmented, and mixed reality devices: Oculus Rift, HTC VIVE, HoloLens to not just improve the overall health and safety of the construction people but also to identify and minimize hazardous activities in multiple construction activities of project execution. The detailed descriptions of activities of technologies and their activity type usage are provided in Table 3, table being extracted, adapted, and modified from multiple journal sources.

Table 3: Modern Construction Safety Training and Delivery Methods, adapted and modified from [Alsharef et al., 2020]

Delivery Methods	Descriptions	Example References	Activity Type	Technology used
1. Game Technology-based Safety Training	To safely perform such building operations or scenario-based simulations, game engine technology builds a 3D virtual world. The 3D world can be viewed on a computer or through virtual reality goggles.	Guo et al. 2012; Li et al. 2012; Lin et al. 2018; Mo et al. 2018; Zhao and Ye 2012	Mobile cranes- lifting and conveying, Tower cranes- erecting, handling, lifting, conveying, dismantling, Excavators-moving and excavation, removing roof panels, drywall finishing, painting, plastering	3DVIA Virtools (a game engine) and Unity 3D application
2. Mixed Reality (MR) Safety Training System	Integrating tracking system, game engine, and VR goggles in creating a virtual construction environment on the googles.	Bosché et al. 2015	Working at heights: roofing, scaffolding, steel erectors, steeple-jacking, painting, bricklaying, and decorating work	6-DOF Head Tracking System integrated with Unity 3D and Oculus Rift
3. System for Augmented Virtuality Environment Safety (SAVES)	A high-fidelity 3D environment was developed to immerse workers in different work scenarios and assess their hazard recognition skill	Albert et al. 2014a	Maintenance and construction in oil and gas facility and general construction in Fluff pulp processing facility	Designed using 3DSMax and rendered through the MAYA software based on UKD game engine
4. Immersive Virtual Environment (IVE)	A 3D Virtual construction site environment is displayed on an Immersive VR power-wall and can be seen through active glasses	Sacks et al. 2013	Cast-in-situ concrete, crane work, steel formwork, stone cladding work,	Revit, 3D studio MAX, and EON Studio v6

Delivery Methods	Descriptions	Example References	Activity Type	Technology used
5. Personalized safety Training using Eye-Tracking	Leveraging computer vision and eye-tracking technologies in developing personalized hazard recognition training	Jeelani et al. 2018a; Jeelani et al. 2018b	Overall construction-related hazards	Wearable eye-tracker (Tobii Glasses 2) on a 3D point cloud
6. Participatory Videos (PV) Intervention Training	Workers are filmed acting while performing certain operations. Then, the video is displayed and discussed during the training session (bottom-up approach)	Lingard et al. 2015	Overall health and safety improvements	Focused on video-based interventions
7. Peer-led Training	Workers receive safety training from their experienced peers	Sinyai et al. 2013; Williams Jr et al. 2010	Roofing, drywall installation, painting, and repairs on ladders	No specific devices used focused on OSHA based vocational training
8. E-learning tools	Use of the internet or storage media (e.g., CD) to deliver health and safety training (video lectures, readings, and interactive tools)	Acar et al. 2008; Ho and Dzeng 2010	Falls from height, floor opening, ladders, roof openings, floor and roof edges, scaffolds, building girders, falls while jumping to a lower level	No specific devices were mentioned, but used virtual pilot classes were for training
9. Naturalistic Injury Simulation (NIS)	Live safety demos are demonstrated resembling actual construction injuries using artificial body parts. The demos target the workers' emotions	Bhandari and Hallowell 2017	Not relevant (we are not looking into simulation in this research)	Not quite relevant
10. 360-Degree Panorama Safety Training	Actual 360-Degree images of the construction site are taken, and safety-related layers are augmented for the trainee to detect the site's hazards	Jeelani et al. 2017; Pereira et al. 2018	Overall construction-related hazards	VR HMD, Unity 5.4, and Visual C++

CHAPTER 3

METHODOLOGY

Introduction

The study aims to investigate the extent to which 3D design while implementing a VR device helps hazard recognition and impact minimization for the user (trainee). Therefore, the survey was conducted with construction professionals with the help of Qualtrics. The questionnaire consists of demographics, construction activities, safety professionals and activity hazards, safety training, and lastly use of technology to mitigate hazards questions. The idea of this survey study was to examine whether adopting BIM, VR, AR devices together affect construction hazards identification and impact minimization on the user. The results of this survey could be helpful to construction practitioners in the industry to improve project execution practice by improving behaviors on hazardous scenarios and establishing safety practices before the actual construction.

The research methodology adopted for this study is based on literature review and a case study approach that tested BIM-based VR simulations using 3D models of hazardous scenarios occurring on four different construction activities selected as part of this research. To begin, a study of the literature was done to look at the issues of hazard identification and minimization approaches in traditional safety planning processes from various perspectives. Following that, a state-of-the-art assessment of VDC technologies was conducted, and the influence of 3D BIM and VR on enhancing construction safety was investigated. The findings prompted an investigation into the possibility of VR-based 3D simulation to improve risk assessment, hazard identification, minimization, and safety training in certain construction sectors.

Hazards which occurred throughout four different major construction activities in the project were investigated throughout this study. A mixed-method research approach was used, which included 3D visualization and a survey (questionnaire) for industry professionals. The mixed methods research approach was selected since it is best suited for research that collects both qualitative and quantitative data simultaneously. The study's primary goal was to create BIM-based models that might be used to create a virtual reality simulation. The BIM-based VR simulations were created to fulfill OSHA's safety planning standards and adhere to the regulations to ensure safety hazards prevention.

Survey Population

Professional experts in the engineering and construction industry were the target demographic. This study employed random industry experts from four specific construction activities and their companies in six different states and civil engineering and construction students from Georgia Southern University to comprehend and assess the potential of BIM and VR devices as the core applications level for these activities. These groups were chosen because of their relevance and usage of VDC tools and knowledge of current construction safety trends, implying that they would offer valuable and accurate input. Qualtrics was used to create and deploy the questions, and respondents were sent a link to the survey via Qualtrics website and emails. All construction professionals (project managers, assistant project managers, safety engineers, contractors, and subcontractor's professionals), including civil and construction management students, were strongly encouraged to participate in the survey. Civil engineering and construction students from courses like "Project Planning and Scheduling" and "Building Information Modeling" participated in this survey. These students were in the Spring 2021, Summer 2021, and Fall 2021 semesters of civil engineering and construction from Georgia Southern University. Some of these students did not have prior experience of the construction fieldwork, including the hazard identification using VR devices. The remaining construction professionals, in contrast, had field experience, including hazard identification training in an immersive virtual environment to some extent. The students had prior hazard identification knowledge through textbooks or classroom material presentations and some from the previous internships or work experiences, but not the skills of using VR devices.

In addition, around 2,400 emails of industry professionals from different construction trades were uploaded in Qualtrics for a survey. The survey was distributed among project managers, safety managers, and administrative officials related to this industry. The survey is then deployed in Qualtrics for various construction professionals or construction companies specific to mechanical, electrical, concrete, and roofing work activities within six different states including the state of Georgia.

Defining Variables

The survey study aimed to investigate the research question, whether the identification and elimination of construction hazards would be significant with the coupling of BIM and VR devices. The dependent variable in this research was the overall safety hazard identification of the construction project activity, while BIM and VR devices usage were considered the independent variables.

The dependent variable was measured by surveying the industry people on four different trades as per the case studies created and who have been exposed to BIM and VR devices together thru their company. Safety training, technology usage/advanced device training, and overall perceived performance constituted the three dependent variables of this study. The mean of four survey questions was used for ‘safety training.’ The mean of nine questions was composed of ‘technology usage/advanced device training.’ One question comprised the ‘overall perceived performance’ dependent variable. The three survey questions about participant demographic characteristics represented the study's independent variables.

Independent variables

- Primary type of construction activities
- Having safety engineer/manager on site
- How do you approach if any safety hazards occur on the job site?
- Hazards during concrete works
- Hazards during roofing works
- Hazards during Electrical Equipment works
- Hazards during Mechanical Equipment works
- Plans for any specific safety improvement

Dependent variables

- Safety training
- Technology used and the advanced device training
- Overall perceived safety performance

Methodology Flowchart

In the beginning, OSHA data was thoroughly reviewed in six different states around Georgia to determine the most dangerous construction activities. In addition, actual recorded safety data from two different companies (performing on major airport construction and a paper manufacturing plant construction) were carefully analyzed to develop another case for this research. Four major case studies were developed because of this approach. Four distinct 3D models were created in Revit for each of the resulting construction activities (tasks), along with three to four hazardous scenarios in each model. The virtual reality headsets were used to view the 3D models in the virtual environment to determine any dangers were possibly present. Therefore, the researchers put this method to the test. Qualtrics was used to create a set of questions to collect prospective responses from industry professionals concerning the usage of 3D BIM and VR devices to identify and mitigate dangers. To evaluate the statistical analysis and the p-test through the p-value approach, the data supplied from Qualtrics was examined using Excel and SPSS software. Then, in the further stages of the research, the findings of the quantitative/qualitative analysis and conclusion were assessed. The schematic of the research methodology is depicted in Figure 6.

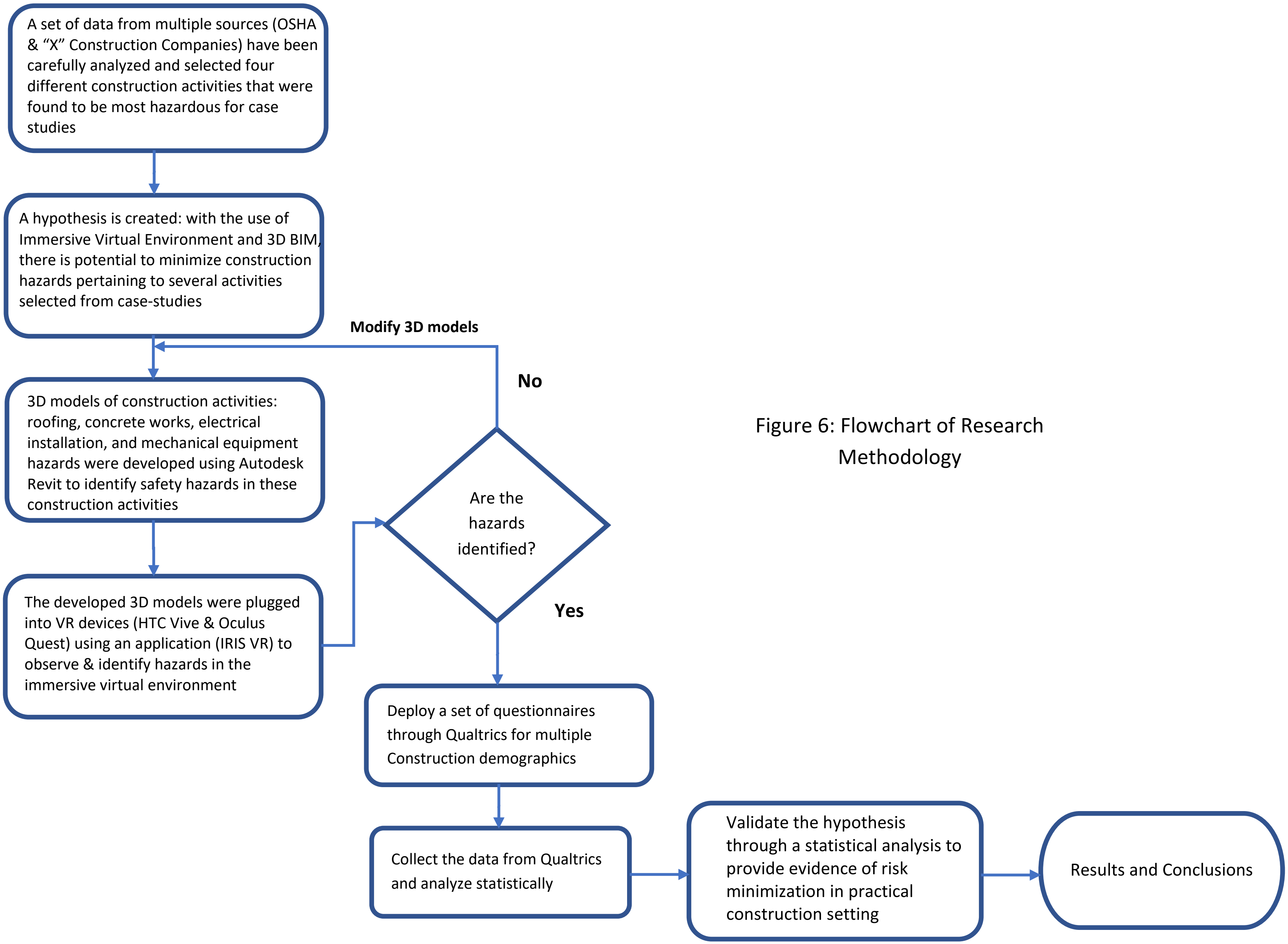


Figure 6: Flowchart of Research Methodology

The research methodology adopted for this study is based on literature review and a case study approach that tested BIM-based VR simulations using 3D models of hazardous scenarios occurring on four different construction activities selected as major construction research work. To begin, a study of the literature was done to look at the issues of hazard identification and minimization approaches in traditional safety planning processes from various perspectives. Following that, a state-of-the-art assessment of VDC technologies was conducted, and the influence of 3D BIM and VR on enhancing construction safety was investigated. The findings prompted an investigation on the possibility of VR-based 3D simulation to improve risk assessment, hazard identification, minimization, and safety training in the major construction sectors.

Hazards that occurred throughout four different construction activities in the project were investigated in this research. A mixed-method research approach was used, which included 3D visualization and a survey questionnaire for industry professionals as part of this methodology. The mixed methods research approach was selected since it is best suited for research that collects both qualitative and quantitative data simultaneously. The study's primary goal was to create BIM-based models which may be used to create a virtual reality simulation.

Selection of construction activities

The research began with gathering information on construction hazards encountered on an actual building project based on OSHA data from the last quinquennium (2015-2020). Construction projects include many different construction operations, activities, and design components. However, the researchers picked only four major construction activities for the case study approach.

The researchers carefully sorted data from the OSHA website published between 2015-2020. The analyzed data were from six different southeast states of the United States: North Carolina, South Carolina, Georgia, Alabama, Tennessee, and Florida. The comments posted by the OSHA inspectors were carefully read and then identified their construction activities for the reported hazards. This process helped the researcher to identify the most hazardous activities and the researchers selected four major construction tasks as part of the case-studies. The construction trades as part of the case-studies are roofing, concrete, electrical equipment, and mechanical equipment works. This data was later categorized into “OSHA-Four,” (OSHA-4) i.e., falls, electrocution, caught-in-between, and struck-by as actually considered by OSHA. Table 4 represents the actual data from OSHA, which is categorized based on OSHA and the construction trade. The possible identified safety hazards on different construction activities are shown below.

Table 4: Possible hazards Classified on Four Different Construction Activities

Construction Activities	**Possible safety hazards**
1. Roofing work	Falls from the roof
	Exposure to the sun
	Injuries from the hand tools
	Improper use of the equipment
	weather conditions
	losing awareness of the edge
	Holes in the roof
	Improper training
	ladder security and placement
2. Electrical wok	Improper safety (PPE)
	Hit by a construction truck
	Exposed wires around the site Powerlines
	Fixing electrical devices at the site
	Electrical shock Hand tool
	Injuries by the falling electrical objects
	Lifting injuries (back strain or back problems)

3. Mechanical work (Cranes, scaffolding, and other mechanical devices)	Falling objects
	Mechanical failure
	Electrical hazards
	Hit by moving vehicle
	Falls from height
	Unsafe access due to stairs or ladders
	Injuries from falling tools
	Electrocution
4. Concrete works (pouring, chemical spills)	Lack of Personal protective equipment (PPE)
	Exposure to chemicals
	Hazards from Power and cutting tools
	Falls from height
	Toxic gases & chemical spills
	Personal injuries
	Chemical burns
	Respiratory illness
	Injuries from falling objects
	Fatalities from moving vehicles

Severe injury reports were collected from a 5,642 data set from OSHA, based entirely on the surrounding six different states, including the state of Georgia, data being collected from 2015 to 2020 timeframe. From 120 construction companies associated with construction activities within Georgia, 3,077 data points were thoroughly examined. These data sets were again carefully sorted on only four different construction activities that were considered part of this study. The activities include roofing, concrete, electrical equipment, and mechanical equipment works only. Based on the feedback from the OSHA inspector, the construction incidents were lastly categorized into "OSHA FOUR" categories which is presented in the Figure 7.

- Falls- 47
- Caught-in-between- 13
- Struck-by- 48
- Electrocution- 15

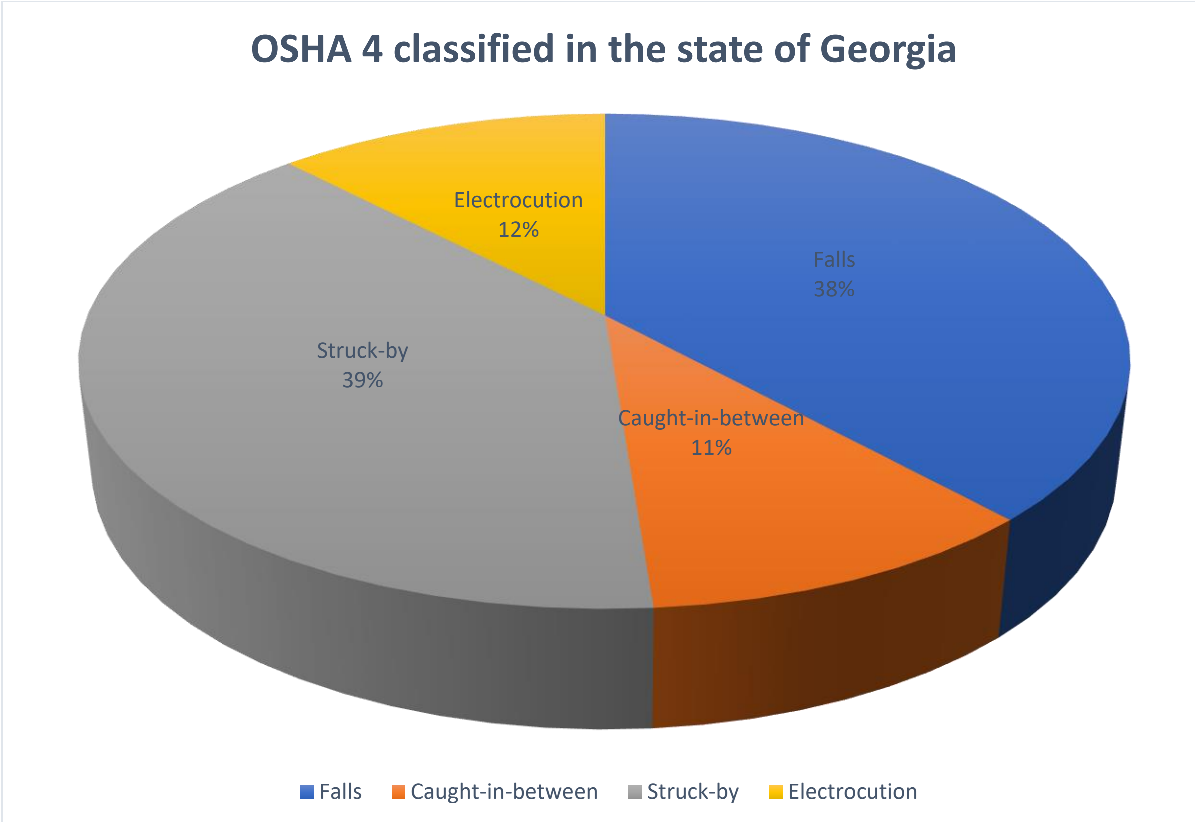


Figure 7: Pie chart of the hazards classified based on OSHA-Four

Out of many construction trades, only four different activities: concrete, roofing, electrical, and mechanical equipment work related to the major construction that were most hazardous were carefully selected for the case studies. Out of these activities, there were 47 different falls related hazards which consists of 38% of overall recorded hazards in the state of Georgia. For instance, OSHA inspector recorded a worker falling from a ladder while working on the anchors was recorded in the fall's category. Another, 48 (39%) hazards were recorded in the struck-by category. Followed by 15 (12%) hazards recorded in the electrocution and the least 13 (11%) caught-in-between hazards were recorded which is shown in Figure 7.

Based on the findings, 26% of the hazards were related to electrical equipment's works, 24% of the hazards were related to the roofing works, 8% to the concrete work, and finally 7% were mechanical equipment works. The "Unknown" 35% may be related in between these activities. The comments in the OSHA data were not clear enough to categorize in any of these activities. The following four construction activities were selected as part of the methodology based on the extracted data. “Unknown” in Figure 8 refers to the incidents classified as hazardous activities but not precisely sure during what construction activities the hazard occurred.

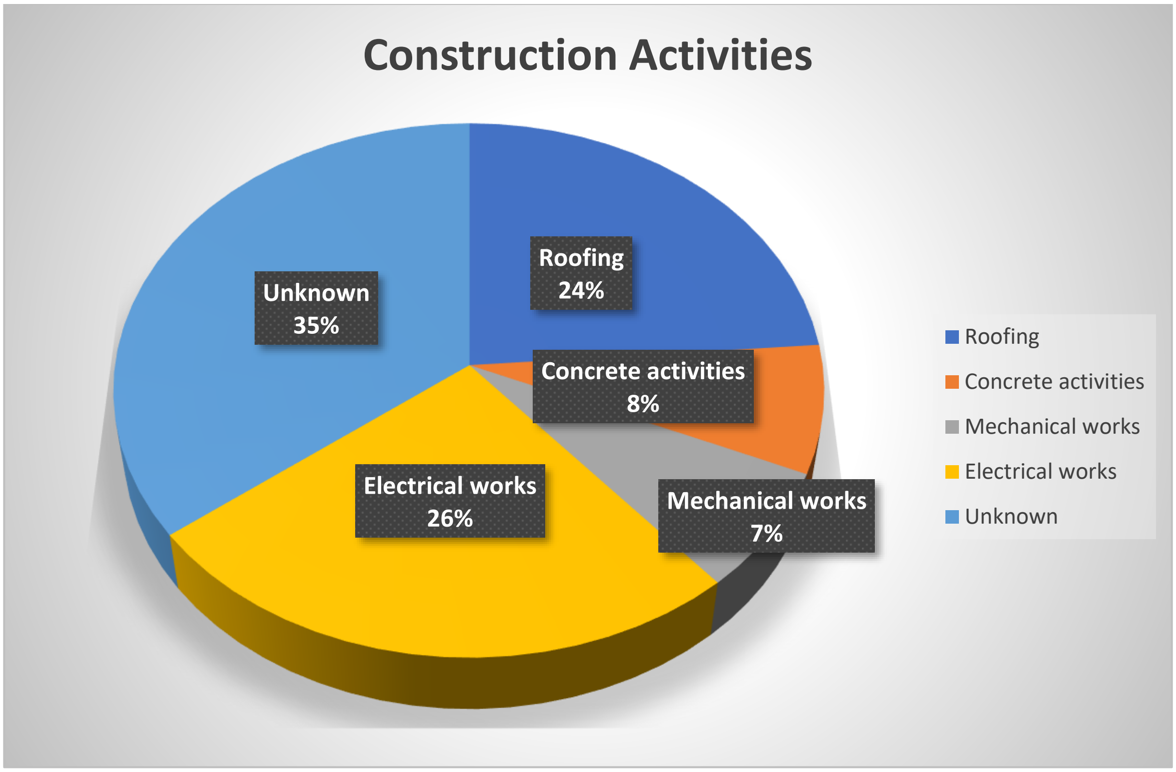


Figure 8: Representation on the percentage (%) of construction trades that were found to be hazardous by OSHA in six different states

In addition to OSHA, another 4623 sets of data from an industry company (X) were meticulously sorted. Out of this data, only 1791 data were further considered for this research and evaluated to detect possible building construction hazards. This company calculated a safety percentage score for all construction operations during site inspections. Because the minimum score ranged from 0 to 35, these data were not further examined. The researchers were primarily interested in safety scores ranging from 40 to 75 because these were the most concerning. A safety score of 75 or above was deemed satisfactory in the workplace. The remarks made in the workplace were carefully recorded to pinpoint the potentially dangerous building operations. Masonry, concrete, drywall, electrical, flooring, framing, HVAC, installation, roofing, siding, tile work, and trim work were the most dangerous among all construction operations, as shown in Figure 9.

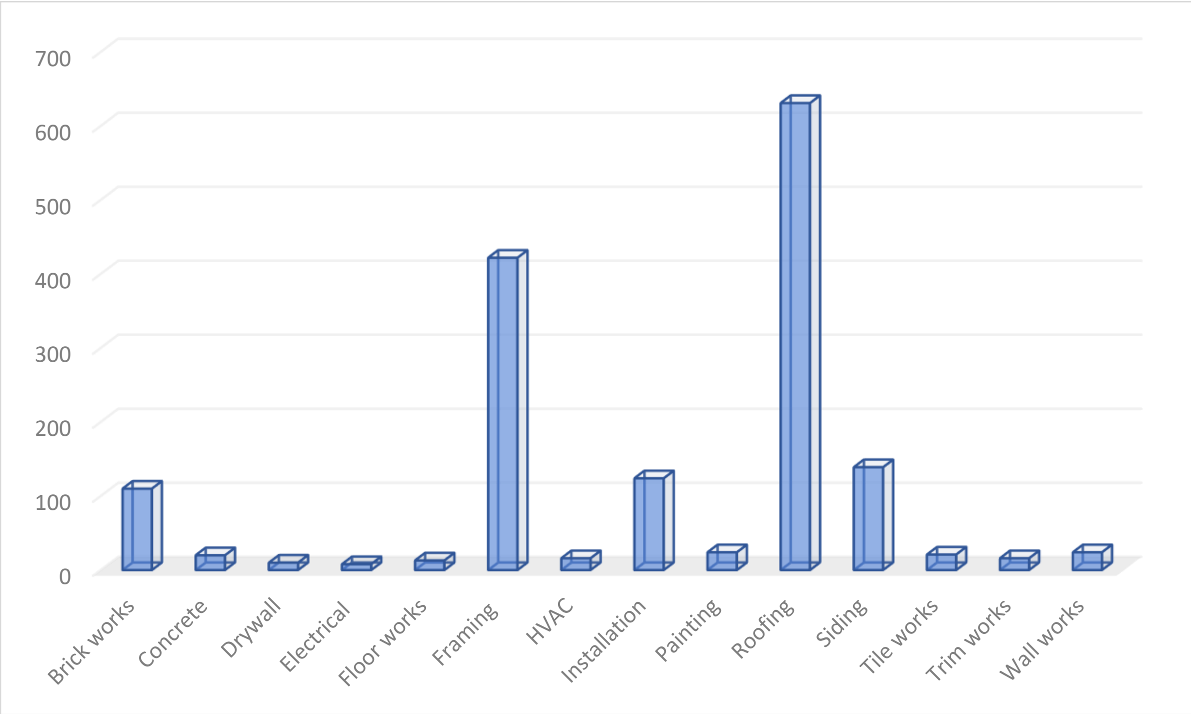


Figure 9: Bar Graph of major construction activities from Company “X”

Survey Questionnaire

A preliminary questionnaire was created to look at the possibilities of VDC/VR for enhancing construction safety. The questions were written so that they would generate the desired response rate, and the questionnaire's simplicity made data collecting easier. This questionnaire was sent to a select group of specialists from both industry and academics for checking any errors and validation of the questions. Various content, sequencing, and data collecting approaches were discussed throughout this pilot survey project. These insightful ideas and feedback received were later incorporated into the final questionnaire.

After incorporating all the recommendations, the final questionnaire was created after applying the suggested modifications. The content and style of the questionnaire were straightforward to comprehend, which encouraged respondents to complete it. The questions were developed in a logical order, beginning with fundamental demographic inquiries, and working their way up to digital design technology and building safety principles. Using Qualtrics platform, the final generated questionnaire was delivered to the civil/construction engineering students and industry professionals. After a certain requisite response rate was met, the data was statistically examined to derive conclusions.

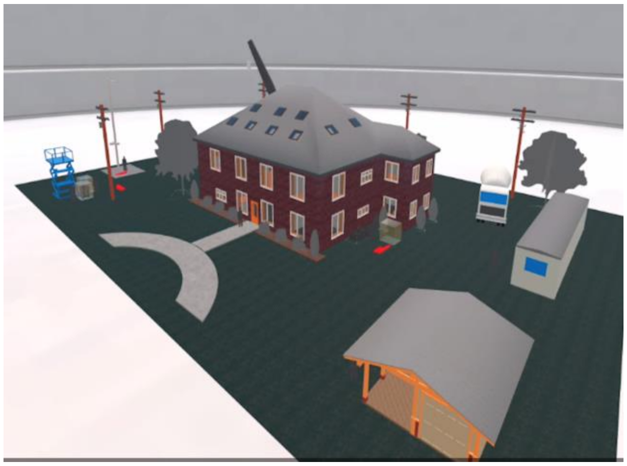
The survey consists of 30 questions deployed using the Qualtrics application. However, at the beginning, a form and survey questions were sent to the Institutional Review Board (IRB) for the verification process. Later, the questionnaire was reviewed and approved by the University's Office of research which is presented in Appendix 1: Survey Questionnaire. These questionnaires included five survey categories: The first category targeted the demographics question: type of construction company, type of construction projects, role as a person in the construction company, while the second category focused on the type of construction activities mainly carried out by the companies which included a couple of questions. The third category targeted the safety professionals and hazards on the performed construction activities. It included nine questions. The fourth category consists of safety training and mitigation of hazards in about five questions. Finally, the fifth category focused on implementing the technology devices for safety training and identifying/recognizing and reducing hazardous activities occurring on the construction projects in about ten questions. The purpose of these categories was to compare all the responses and evaluate whether adopting BIM and VR devices together had a significant statistical effect on project hazard identification and elimination.

Developing 3D models and placing hazardous scenarios on each case study

Four separate case studies with 3-5 hazardous scenarios are created in the 3D environment. In the obtained 3D models, there are hazardous situations involving electrical hazards such as lifting items around electrical wires, being hit by construction equipment to the electrical pole and exposed electrical cables surrounding the construction site. Hit by a vehicle or excavator on the job site, struck by mechanical equipment while working on the job site, and many more mechanical related hazards scenarios also exist in another 3D model. Falls from the roof when installing or removing shingles, improper ladder placement, weather conditions, and missing PPE are all examples of roofing hazards, and this has been portrayed in the 3D model. Finally, concrete hazards included being struck by a concrete truck during pouring, concrete cutting, chemical hazards from the smell or touching fresh concrete, and improper concrete placement on construction sites. All four 3D models ((a), (b), (c), & (d)) as per the case-studies are presented in Figure 10. As stated above, three to five distinct risky and unsafe situations related to these activities are included in the 3D model for visualization in the virtual environment. The roofing works include hazardous scenarios from moving materials for roofing work and installing solar panels or shingles on the roof, lifting roofing materials using mechanical devices, a worker without following OSHA guidelines (not properly fixing on anchors) while working on the roof or a worker without PPE while performing roofing works, falls due to weather conditions while working on the roof and lastly hazards due to unbalanced ladders on the construction sites.

The electrical work includes hazards being hit by an excavator, or tower cranes going into the power lines, caught in between electrical equipment, hazards due to naked (exposed and energized) wires lying on the ground, installing transformer/HVAC units into the building or aside the building sites, and electrocution while installing electrical appliances into the building. The concrete work includes hazards from being hit by falling material from a lifting tower, caught in between mechanical devices while doing concrete work, pouring concrete into deep foundations (chemical burns), and being hit by a concrete truck or an excavator into a narrow construction site. Lastly, mechanical works include hazards being hit by an object when lifting using a mechanical device (for instance, tower cranes), loading and unloading materials from a truck by a mechanical device (like forklifts), caught-in-between due to poor visibility by trucks, dozers, excavators, and hazards with the forklifts which is presented in the APPENDIX 2.

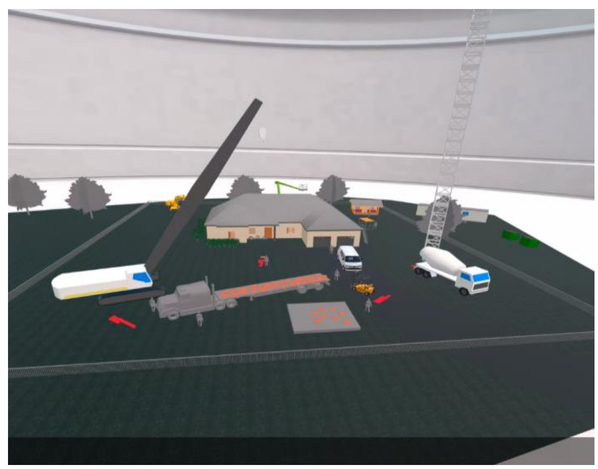
These models have been tested in the virtual environment using Oculus Quest 2 HMD. The specifications of HTC VIVE PRO and the Oculus Quest 2 are shown in Table 5. The IRIS VR platform was used to integrate the 3D models into the VR headset. The flowchart of the workflow is shown in Figure 11. Once the 3D models were placed in the VR headset, the researcher was able to walk around the virtual environment and view the possible safety hazards occurring to the different construction activities.



(a) Electrical equipment works

(b) Concrete works

(c) Roofing works



(d) Mechanical equipment works

Figure 10: Finalized 3D models for all four case-studies

Table 5: Lists of Virtual Reality devices used for VR case studies

	Oculus Quest 2	**HTC VIVE**
		
Company Name	Facebook	HTC
Field of view	89 degrees	110 degrees
Max Resolution	1832 X 1920	2160 X 1200
Display Type	Single-Fast switch LCD	OLED
Pixel Density	456 ppi	461 ppi
Weight	503g	563g
Platform	Oculus Home	Steam VR, VIVE port
Headset Type	Tethered	Tethered
Max Refresh Rate (Hz)	72	90
Multiple Users	Yes	Yes
Controller	Oculus Touch, Xbox One	VIVE controller
Head Tracking	Inside-Out Tracking	Outside-In Tracking
Primary input device	Controllers	Controllers
Portability and setup	Medium	Hard
Processor	Qualcomm Snapdragon XR2 Platform	Intel i5 or AMD Ryzen
RAM	6GB	4GB
Battery life	2-3 hours	Approx. 6 hours
Storage	64 GB or 256GB	up to 2TB
Strap	Soft	soft

Autodesk Revit 2021 was used to create the 3D models of all four residential building as per the case studies. The IRIS VR plugin was installed in Revit, allowing researchers to upload 3D models for viewing in the virtual environment. IRIS VR serves as a gateway between two points. There are, however, a wide variety of different plugins that may be used to connect 3D models with VR devices. Because Oculus Quest 2 was available in the BEaM VR/AR laboratory, the researchers preferred to utilize IRIS VR for 3D model testing because it is more user-friendly and has more features than other tools. HTC was not used to test the models in the lab because the process of integrating 3D models into the virtual environment with HTC is more complicated than the Oculus Quest 2. The account was registered into the Prospect, which is part of the IRIS VR, using the university email. Once the email was completed, the researcher is able to upload the 3D models from Revit to the Prospect and wait around 30 seconds to synchronize. Using the same login credentials, one can now access the Oculus headset and merge it into the virtual environment, where users can see and wander around the models. The procedure/flowchart of integrating 3D models into the VR headset is illustrated in Figure 11.

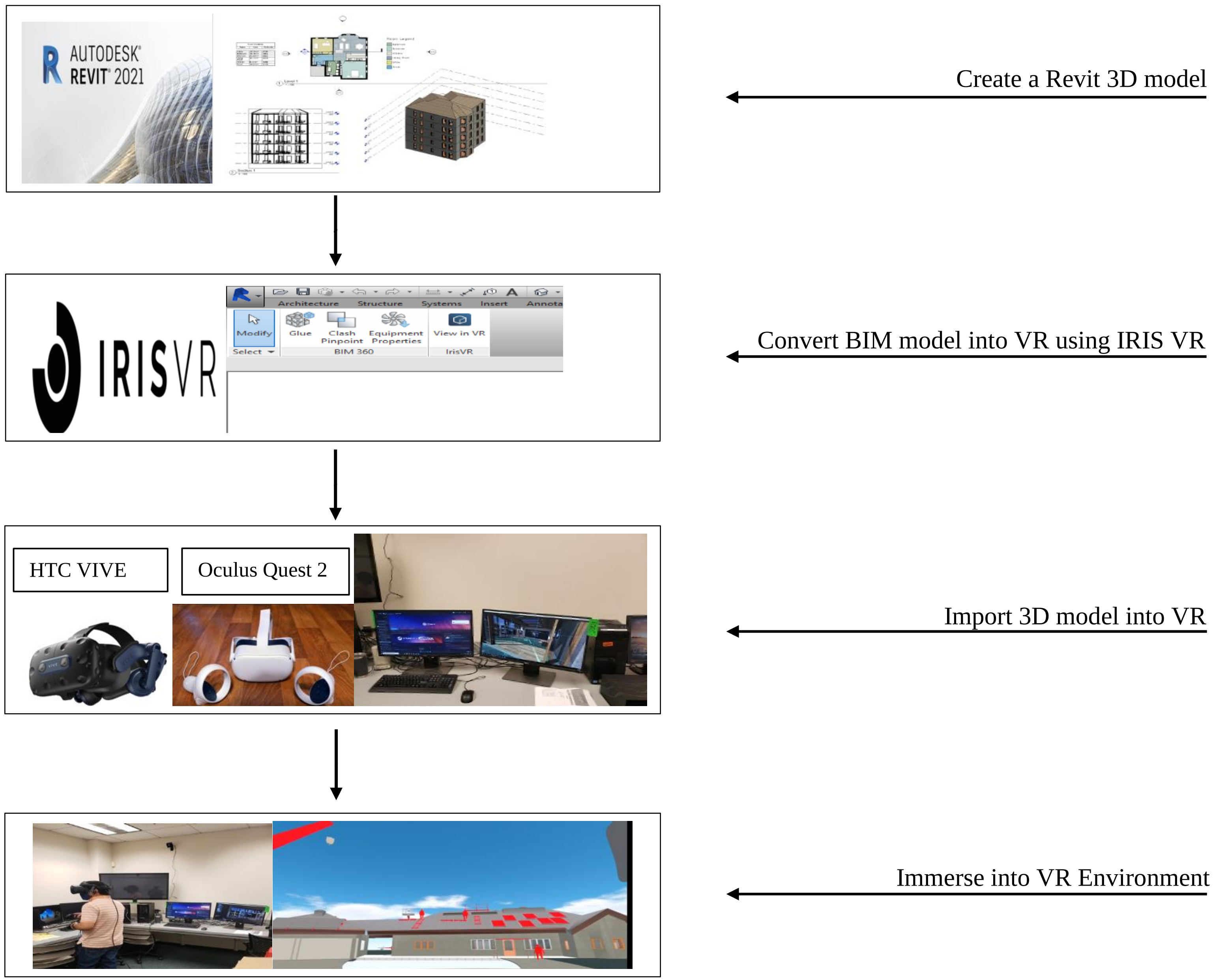


Figure 11: Flowchart of integrating 3D models into VR HMD

CHAPTER 4

DATA ANALYSIS

Introduction of the Data Analysis

The survey consists of both quantitative and qualitative questionnaires. The collected data from the survey were analyzed using statistical analysis. In addition to this, the case studies were created based on the data supported from multiple construction companies. The case studies consisted of data related to the safety hazards occurring at the construction sites. This data was also analyzed, and hazards identified were supported by construction activities which were most prone to have hazards. The mean, variance, and standard deviation of the data were calculated. Finally, the results were tested and later validated using the chi-square test and then the conclusions, and future recommendations were written. In the numeric description, the quantitative approach proved helpful in determining the participant's opinions. Qualtrics survey software was used to send the survey to random samples of construction-related professionals.

According to several participants, BIM plays an essential role in detecting hazards. Some believe that due to its ability to record every aspect necessary in the development of a project, down to the most minute detail, it assists in identifying possible construction hazards and is particularly useful in hazard management. Those that do not use BIM, on the other hand, claim to search project plans and other valuable images before and throughout construction to find any safety-related flaws. Others argue that instead of BIM, skill and attention should be used. Although many participants stated the advantages of BIM, they do not currently use the technology.

Project managers were questioned about the benefits of using BIM and VR devices and if they had assisted in identifying safety hazards. The Project Managers who had used BIM unanimously agreed that both BIM and VR devices had improved hazard identification in the construction process, allowing for better planning of safety-related concerns, eliminating errors in the 3D design, and fewer safety incidents during the project execution.

Demographic Characteristics

The survey was distributed through Qualtrics online platform, and targeted random construction-related professionals. A total of 168 survey results were collected from Qualtrics. However, 144 participants worked in varying capacities for construction companies after removing 24 participants who did not answer all the survey questions. For the workplace role question in the survey, 147 responses were collected. The survey results showed that 22 % were related to project management, 24% towards safety management, 9 % were civil and construction engineering students, 15% were assistant project managers, 7 % superintendent, and lastly, 23% were in other categories. Out of 168 survey responses, only 134 professionals completed the type of construction company question. From the survey results, the largest proportion of the construction company, at 47.4% (n = 64) were general contractors while 16.3% (n = 22) were subcontractors, 15.6% (n = 21) were design-build contractors, 8.9% (n = 12) were owner-builders, and the least 0.7% were real estate developers. Exactly 11.1% (n = 15) of the participants said that their construction company fell into the ‘other’ category.

Analysis of Qualitative Data

Academics and industry practitioners were asked three questions for the qualitative analysis. These three questions were open-ended and placed on the research survey. The first questions were regarding the repetitive hazards identified by their company, the second was related to the hazards mitigating strategies, and the last was regarding the design Phase, BIM, and Hazard

Minimization Efforts. The data was carefully looked into in order to identify the eleven focus areas: PPE, Improper use of tools or workmanship, multiple hazards, dangerous conditions, dangerous materials, improper body mechanics, trip/fall hazards, ignore safety plans, distractions, fall hazards, and not specified which is shown in Figure 12. On each question (descriptive coding and concept coding were used as a technique to apply basic labels and to provide an inventory of the identified areas). Therefore, elemental coding was used as the primary approach to this qualitative data analysis. Only first cycle coding technique is performed due to lack of more data labels obtained from the survey questions.

Repetitive Hazards

At first, participants were asked if they had any repetitive hazards identified by their company. Exactly 31.9% (n = 52) said that they did while 22.7% (n = 37) said that they did not. They continued to identify those hazards that were subdivided into 11 different main categories. The largest proportion, at 22.2% (n = 12), reported that their company's main repetitive hazard had to do with PPE while 11.1% (n = 6) each said it was mainly due to dangerous working conditions or multiple hazards; 9.3% (n = 5) each said their hazards concerned dangerous materials or trips/fall hazards; 5.6% (n = 3) said improper body mechanics; 3.7% (n = 2) reported ignoring safety plans, and 1.9% (n = 1) reported distractions; exactly 9.3% (n = 5) did not specify the source of their repetitive hazards.

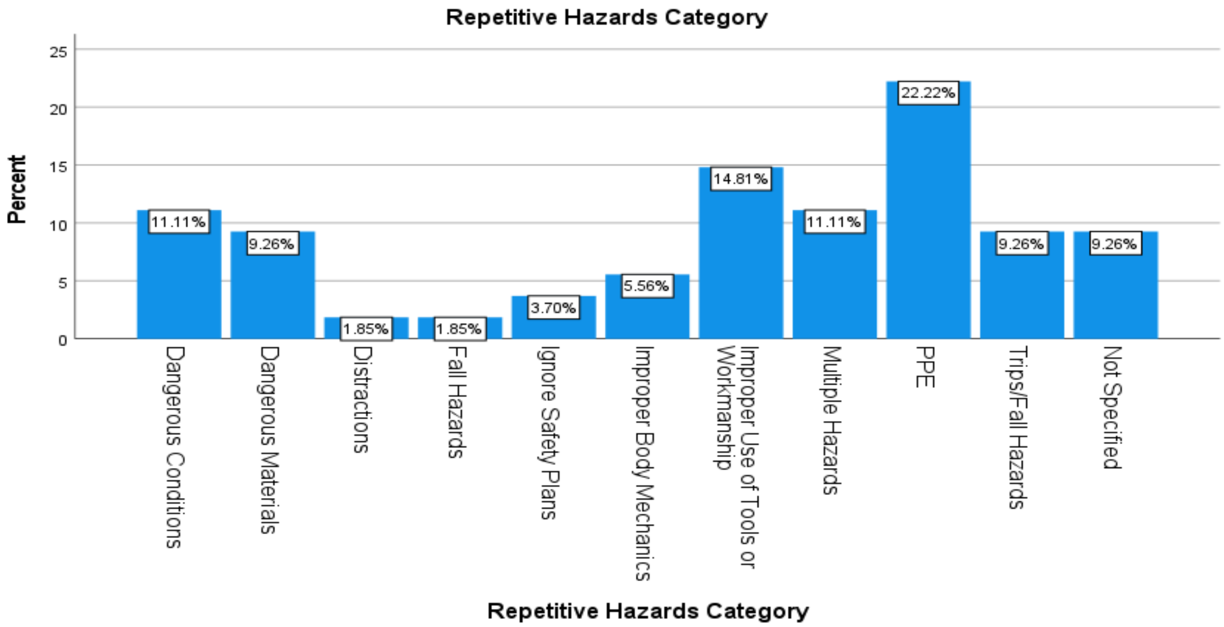


Figure 12: Bar Graph of Repetitive Hazards

Over 22.22% of the participants reported their main repetitive hazard to be concerned with either no wearing or improperly wearing PPE. One said it was a struggle to get workers to wear proper PPE. Others reported inconsistent use and need to remind employees to wear PPE. Over 11% of the participants identified dangerous working conditions as a source of repetitive hazards. The majority cited objects or materials falling from buildings, while a few others mentioned electrical hazards and working near cable utility cords. One said that heights were a hazardous issue. A total of six participants (11.11%) mentioned more than one repetitive hazard. However, the majority did also mention the lack of PPE use as an issue. A few also cited proper use of fall protection and other trip and fall hazards. Misuse of tools and machinery leading to injuries was a concern, while working with dangerous materials such as chemicals was another.

Over 9% of the participants mentioned that dangerous materials were a source of repetitive hazards. Every trade use material can be considered dangerous if proper safety precautions are not taken. Examples provided by the participants include welding, insulation, firestop materials, per- and polyfluoroalkyl substances (PFAS), rebar, and cutting materials that pose risks, such as stones. Again 9.26% of the participants mentioned trips and falls as a source of repetitive hazards. Trips and falls were a re-occurring theme cited by many participants concerning repetitive risks. Some work at elevated levels calls for extra precautions such as tethering and other fall restraint procedures. Others discuss that worker were falling due to minor hazards around the job site leading to injuries. Over 5% of the participants mentioned improper body mechanics as a source of repetitive hazards. Several participants discussed the risks that lifting heavy objects can bring to the job site. In particular, back strains from lifting appear to be primarily common.

However, one participant also discusses how prolonged standing poses safety risks to their organization. About 4% of the participants mentioned ignoring safety plans as a source of repetitive hazards. Two of the participants raised concerns about safety plans being ignored. Subcontractors and other businesses unfamiliar with the job site are mentioned. One relayed how the subcontractor is unlikely to read or acknowledge safety requirements or anticipate them not being reinforced. About 2% of the participants mentioned distractions as a source of repetitive hazards. One of the participants shared distractions as being a source of repetitive hazards. Such distractions included technology such as phones and tablets.

Mitigation Strategies

Participants shared their organization's main hazard mitigation strategies that were further subdivided into ten categories. Nearly one-third (n = 32) rely on safety education while 16.5% (n = 17) hold regular safety meetings; close to 12% cite safety plans as being their primary hazard mitigation strategy; 9.7% (n = 10) each discuss disciplinary actions or enforcement activities; 2.9% (n = 3) have reporting systems; 1% (n = 1) each use incentives or new technology to mitigate hazards; 2.9% (n = 3) of the participants said that their companies did not have any mitigation plans; 13.6% (n = 14) reported that their companies had mitigation strategies, but they did not elaborate on what they were which is presented in Figure 13.

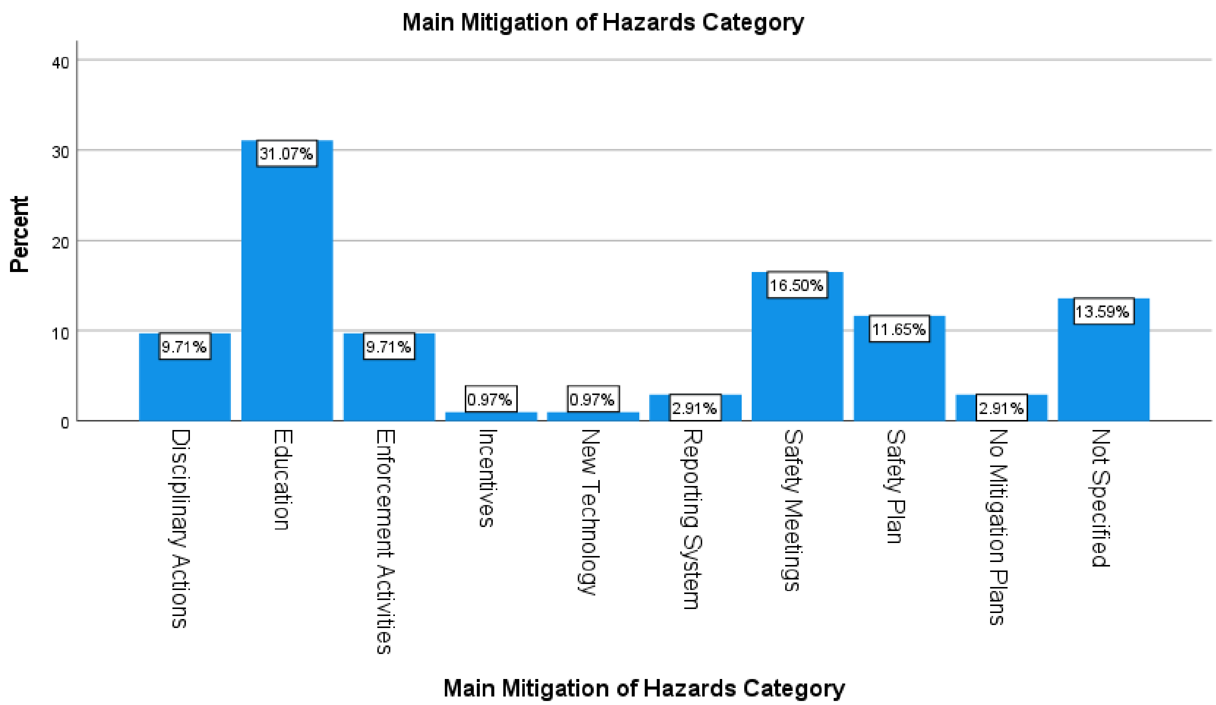


Figure 13: Bar Graph on Main Mitigation of Hazards Category

By far, education in various forms was cited as the foremost mitigation strategy used by the participants. As said by one of the participants, ample training in awareness of surroundings on site is crucial in addition to education regarding various aspects of worksite activities so that awareness can be maintained, and hazards avoided. While safety training was mentioned by several, some also mentioned training and retraining, while others believe in the importance of learning where they are most vulnerable to hazards. Others rely on word-of-mouth. The industry professionals would provide awareness to those less experienced in terms of keeping themselves most safe on the job. However, if they were unsure if the newcomer was fully aware of the hazards, they would not be permitted near the substances or areas that posed the most significant hazards. Others talk about regular training sessions, workshops, and other awareness activities. The theme running through education-related answers pertained to constant training and awareness activities to create a safety culture. Holding regular safety meetings was also a popular mitigation strategy among the participants.

While some formalized the process, others discussed more informal and regular sessions such as “toolbox meetings" to bring constant awareness to the job sites. Others reiterate safety as a priority in daily discussions with subcontractors, while others start their week focusing on safety-related practices. Several participants discussed the importance of having safety plans and other related programs. This aids in the process of identifying, recognizing, eliminating, or controlling job-specific hazards. One even pointed out that this process changes specific to the job. Disciplinary actions were cited to reinforce the culture of safety. While some did call for training during the process, others were less tolerant of any safety violations, including immediate dismissal for those violating safety rules. Others cited enforcement activities to mitigate the job hazards. Such activities included on-site monitoring, random testing, and audits followed by corrective actions. Others felt that reporting systems were essential to the safety of their employees. One proactive approach included a website portal where employees could report hazards. Another organization also stressed the importance of their employees reporting safety-related concerns and encouraged them to do so. Other companies have instilled a financial incentive to retain safety on the job site. For example, the employees of one company receive quarterly bonuses if safety is adhered to, while others simply strive to improve safety-related strategies and mitigation efforts through the employment of new technologies.

The Design Phase, BIM, and Hazard Minimization Efforts

When the participants were asked if they believed in using BIM as a significant player in identifying and minimizing hazards, 48.9% said that they did, while 22.8% said that they did not, and 28.3% did not have an opinion one way or the other. Figure 14 shows the demographic data of the belief that BIM plays a significant role in hazard minimization.

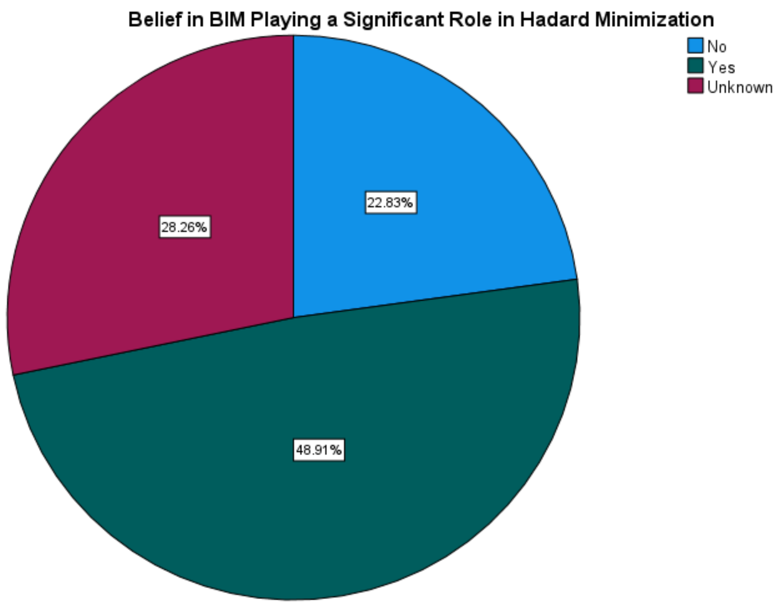


Figure 14: Pie Chart of Belief in BIM Playing a Significant Role

Multiple participants mentioned that BIM plays a massive role in identifying hazards. Some participants shared that it helps them see where failures may occur and that it is highly effective in risk management due to its ability to capture every detail needed in constructing a project down to every last-minute detail. However, those who do not use BIM say that they scour project plans and other helpful images before and during the construction phases to help them identify potential areas of safety-related vulnerabilities. Others cite experience and caution used in lieu of BIM. In contrast, several cited the usefulness of BIM but presently do not involve the technology in their processes.

Analysis of Quantitative Survey Data

The quantitative analysis was carried out using Qualtrics survey quantitative question related data. The survey was open to participants for a period of about six months. The survey was sent to almost 2,400 potential participants, including academics and AEC professionals, to Georgia state and five other surrounding states. Contacts for the survey were gathered through LinkedIn connections and other industry groups, engagement with AEC industry professional groups, and other publicly available contact directories and databases maintained by the University. Additionally, the study was promoted on LinkedIn, the American Society of Civil Engineers (ASCE), the Construction Management Association of America (CMAA), Associated General Contractors of Georgia (AGC Georgia) and their other social media platforms for the AEC industry.

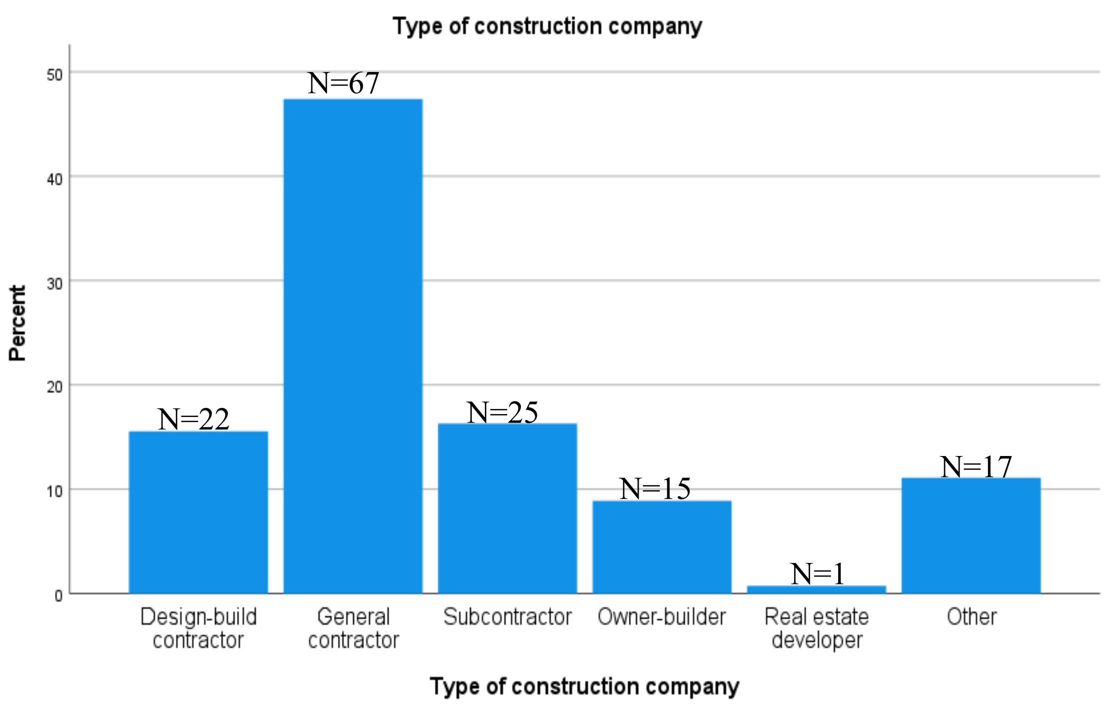


Figure 15: Bar graph of construction company type

The survey result accounted the largest proportion at (N=67) of the company being a general contractor, while sub-contractor at (N=25), and the least (N=1) as the real estate developer which is shown in Figure 15. On the survey, the participants were asked the type of construction projects their company works on. The largest proportion, at 49.6% (n = 67) mentioned commercial building construction while 19.3% (n = 27) residential building construction, 15.6% (n = 23) ‘other’ construction, 11.1% (n = 16) industrial construction, 3% (n = 4) bridge construction, and 1.5% (n = 2) highway construction which is shown in Figure 16.

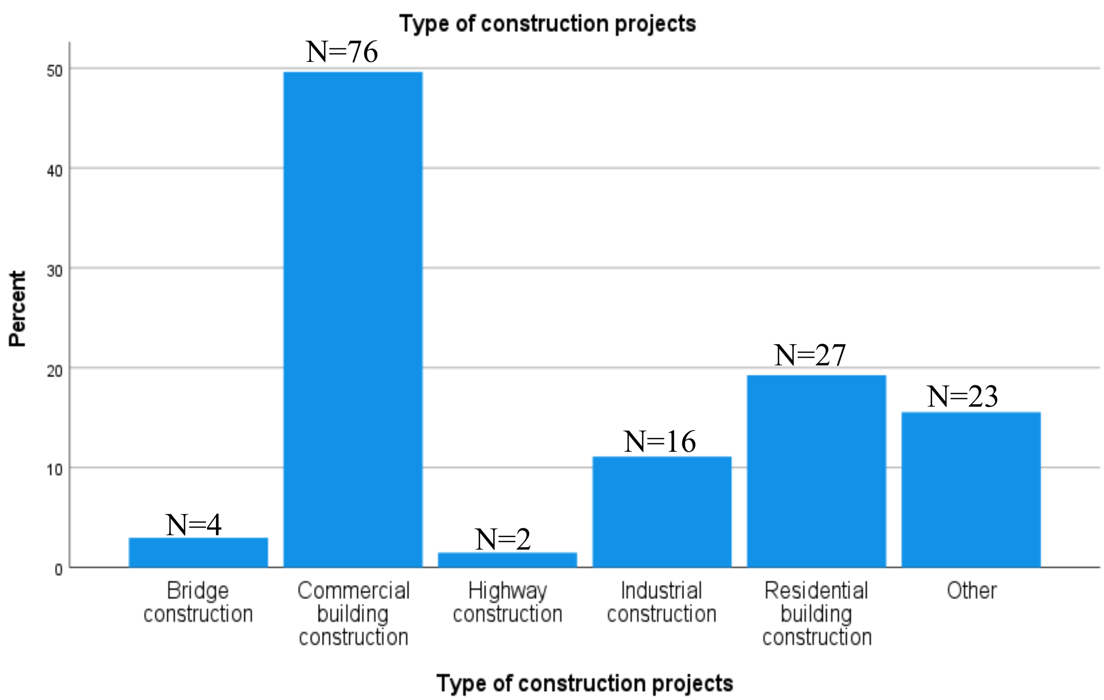


Figure 16: Bar graph of construction projects type

When it came to specific roles within the construction company, the survey results accounted for 23.9% (n = 36) safety managers, 21.6% (n = 29) ‘other’ professionals, 20.9% (n = 31) project managers, 15.7% (n = 22) assistant project managers, 9.7% (n = 13) civil/construction engineering students, and the rest 8.2% (n = 10) as superintendents which is shown in Figure 17.

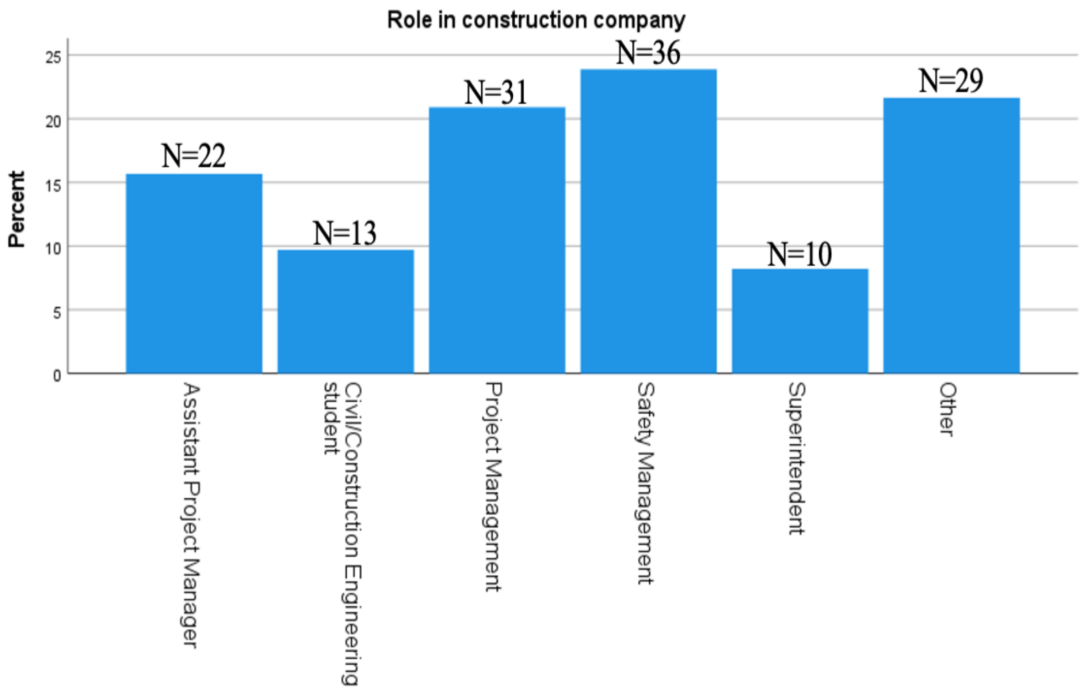


Figure 17: Bar graph of individuals' role in construction companies

Concrete Activities

The survey result shows that 20.63% of the respondents stated safety hazards are related to concrete cutting, while 18.88% of the respondent's stated hazards related to concrete forming and pouring, and the least 4.90% stated the hazards related to the concrete work inspection during concrete activities on the job sites. The detailed information is illustrated by the pie chart from Figure 18 and Table 6.

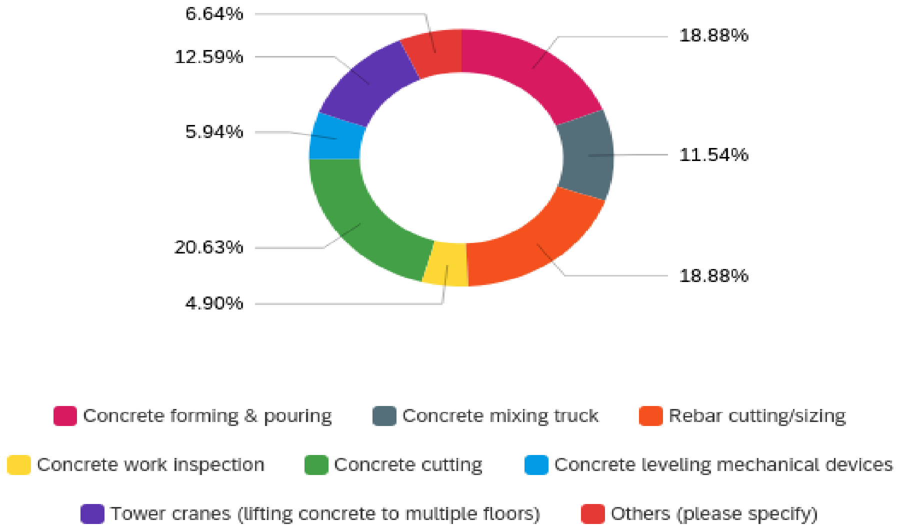


Figure 18: Pie chart of percentages for multiple concrete activities

Table 6: Table of Percentages and Counts for Concrete Works

Answers	**%**	**Counts**
Concrete forming & pouring	18.88%	54
Concrete mixing truck	11.54%	33
Rebar cutting/sizing	18.88%	54
Concrete work inspection	4.90%	14
Concrete cutting	20.63%	59
Concrete leveling mechanical devices	5.94%	17
Tower cranes (lifting concrete to multiple floors)	12.59%	36
Others (please specify)	6.64%	19
Totals	**100%**	**286**

Electrical Equipment works

From Figure 19 and Table 7, the result shows 27.13% of the respondents stated safety hazards are related to installing electrical cords/ducts switches, while 19.03% of the respondent's stated hazards related to the laying open electrical wires, and the least 8.10% stated the hazards related to the other electrical works.

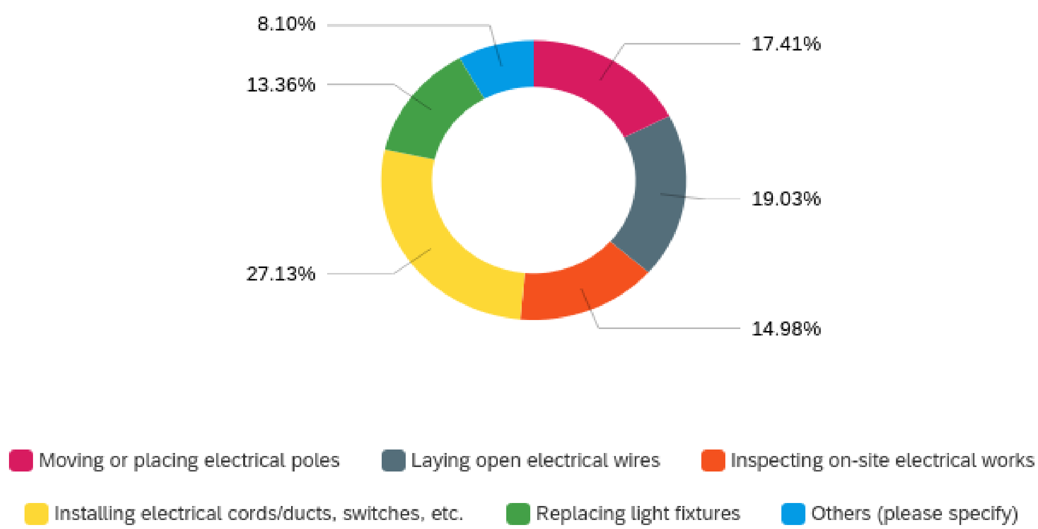


Figure 19: Pie chart of percentages for multiple electrical equipment works

Table 7: Table of Percentages and Counts for Electrical Equipment Work

Answers	**%**	**Counts**
Moving or placing electrical poles	17.41%	43
Laying open electrical wires	19.03%	47
Inspecting on-site electrical works	14.98%	37
Installing electrical cords/ducts, switches, etc.	27.13%	67
Replacing light fixtures	13.36%	33
Others (please specify)	8.10%	20
Totals	**100%**	**247**

Mechanical Equipment works

From Figure 20 and Table 8, the result shows that 22.61% of the respondents stated safety hazards are related to aerial and scissor lift operations, while 20.00% of the respondent's stated hazards related to the operating forklifts. The least 2.32% stated the hazards related to the other mechanical equipment-related works.

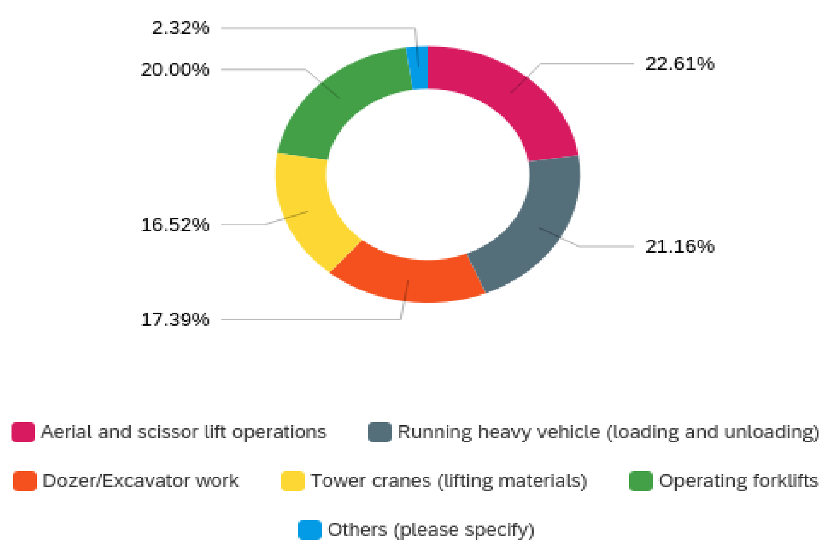


Figure 20: Pie chart of percentages for multiple mechanical equipment works

Table 8: Table of Percentages and Counts for Mechanical Equipment Works

Answers	**%**	**Counts**
Aerial and scissor lift operations	22.61%	78
Running heavy vehicle (loading and unloading)	21.16%	73
Dozer/Excavator work	17.39%	60
Tower cranes (lifting materials)	16.52%	57
Operating forklifts	20.00%	69
Others (please specify)	2.32%	8
Totals	**100%**	**345**

Roofing works

From Figure 21 and Table 9, the result shows 24.78% of the respondents stated construction hazards are related to installing trusses while 21.24% of the respondent's stated hazards related to the working anchors from the roof edge, and the least 8.41% stated the hazards related to the other roofing related works.

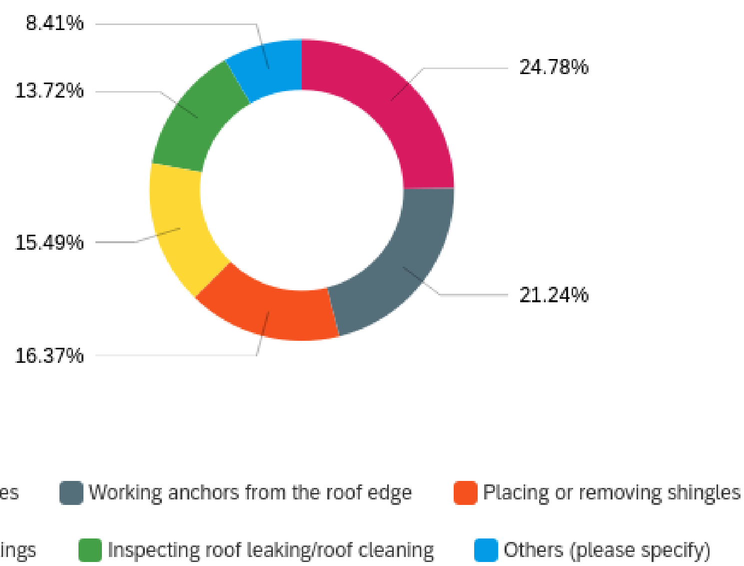


Figure 21: Pie chart in percentage for multiple Roofing works

Table 9: Table of Percentages and Counts for Roofing Works

Answers	**%**	**Counts**
Installing trusses	24.78%	56
Working anchors from the roof edge	21.24%	48
Placing or removing shingles	16.37%	37
Placing ceilings	15.49%	35
Inspecting roof leaking/roof cleaning	13.72%	31
Others (please specify)	8.41%	19
Totals	**100%**	**226**

Hypothesis Testing

The collected Qualtrics survey data was nominal. A nominal data is data that may be labeled or classified into mutually exclusive groups. Normality of data was established in addition to the satisfaction of any assumptions prior to running any of the analysis. A normal distribution, often known as the Gaussian distribution or the bell-shaped curve, is a type of statistical distribution. The mean and standard deviation of the data define the normal distribution, which is a symmetrical continuous distribution. Therefore, to establish association, the chi-square test for association was used. The chi-square test of independence is used to determine if two nominal (categorical) variables have a significant relationship. Each category's frequency for one nominal variable is compared to the categories of the second nominal variable. The data may be shown in a contingency table, with each row representing one variable's category and each column representing the other variable's category. In cases where cell counts were less than five, Fisher’s exact test was used as an alternative. All analyses were calculated with a 95% confidence interval using IBM SPSS Statistics.

The main construction activities that the researchers were looking at in this study were Roofing, Concrete, Mechanical equipment, and Electrical equipment. Framing and other types of building operations were included in the question to provide respondents some flexibility. The analysis does not include the two construction activities mentioned above. Multiple chi-square tests were performed across dependent and the independent variables to see if they are significant. Future study on these or other construction-related activities may be conducted in order to achieve a detailed understanding of the safety hazards.

Table 10: Observed & expected values for safety training with primary type of construction activities

Crosstab

			Primary type of construction activities						
			Concrete work	Electrical work	Framing	Mechanical work	Roofing activities	Other	Total
Safety training	Minimum	Count	0	0	1	1	0	0	2
		Expected Count	1.1	.1	.2	.2	.1	.4	2.0
		% within Safety training	0.0%	0.0%	50.0%	50.0%	0.0%	0.0%	100.0%
		% within Primary type of construction activities	0.0%	0.0%	10.0%	8.3%	0.0%	0.0%	1.6%
		% of Total	0.0%	0.0%	0.8%	0.8%	0.0%	0.0%	1.6%
	Low	Count	8	0	0	2	1	2	13
		Expected Count	7.2	.7	1.0	1.2	.5	2.4	13.0
		% within Safety training	61.5%	0.0%	0.0%	15.4%	7.7%	15.4%	100.0%
		% within Primary type of construction activities	11.3%	0.0%	0.0%	16.7%	20.0%	8.3%	10.1%
		% of Total	6.2%	0.0%	0.0%	1.6%	0.8%	1.6%	10.1%
	Moderate	Count	23	3	7	7	2	12	54
		Expected Count	29.7	2.9	4.2	5.0	2.1	10.0	54.0
		% within Safety training	42.6%	5.6%	13.0%	13.0%	3.7%	22.2%	100.0%
		% within Primary type of construction activities	32.4%	42.9%	70.0%	58.3%	40.0%	50.0%	41.9%
		% of Total	17.8%	2.3%	5.4%	5.4%	1.6%	9.3%	41.9%
	High	Count	37	4	2	2	2	9	56
		Expected Count	30.8	3.0	4.3	5.2	2.2	10.4	56.0
		% within Safety training	66.1%	7.1%	3.6%	3.6%	3.6%	16.1%	100.0%
		% within Primary type of construction activities	52.1%	57.1%	20.0%	16.7%	40.0%	37.5%	43.4%
		% of Total	28.7%	3.1%	1.6%	1.6%	1.6%	7.0%	43.4%
	Very high	Count	3	0	0	0	0	1	4
		Expected Count	2.2	.2	.3	.4	.2	.7	4.0
		% within Safety training	75.0%	0.0%	0.0%	0.0%	0.0%	25.0%	100.0%
		% within Primary type of construction activities	4.2%	0.0%	0.0%	0.0%	0.0%	4.2%	3.1%
		% of Total	2.3%	0.0%	0.0%	0.0%	0.0%	0.8%	3.1%
Total		Count	71	7	10	12	5	24	129
		Expected Count	71.0	7.0	10.0	12.0	5.0	24.0	129.0
		% within Safety training	55.0%	5.4%	7.8%	9.3%	3.9%	18.6%	100.0%
		% within Primary type of construction activities	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	55.0%	5.4%	7.8%	9.3%	3.9%	18.6%	100.0%

A crosstab is performed between two variables (safety training and the primary type of construction activities) in Table 10. On the column, there are different levels of safety training and on the row, multiple construction activities are shown. The observed and the expected values are calculated using this crosstab which is later used to calculate the value of chi-square. Based on the data analysis using the chi-square tests, safety training was not significantly associated with the primary type of construction activities, nor was it significantly associated with the perceived construction activities hazards as, $p > .05$. The p-value can be found using Excel sheet. However, in this research value of p is identified automatically using the SPSS software. The achieved value of p is 0.255 which is greater than 0.05. Therefore, the result suggests that there is no significance between two variables.

Table 11: Results of safety training with primary type of construction activities

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)	Point Probability
Pearson Chi-Square	23.711[a]	20	.255	.[b]		
Likelihood Ratio	24.051	20	.240	.190		
Fisher-Freeman-Halton Exact Test	22.909			.195		
Linear-by-Linear Association	2.379[c]	1	.123	.130	.066	.007
N of Valid Cases	129					

a. 23 cells (76.7%) have expected count less than 5. The minimum expected count is .08.

b. Cannot be computed because there is insufficient memory.

c. The standardized statistic is -1.542.

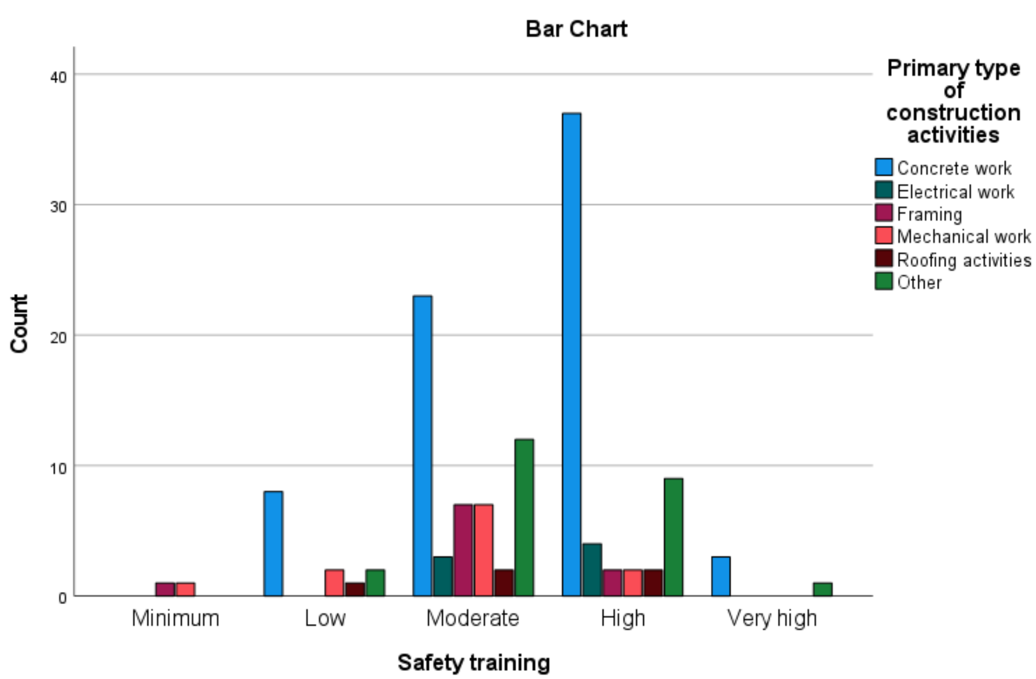


Figure 22: Bar graph of safety training with primary type of construction activities

There were 129 valid participants who responded to the primary type of construction activities question. Based on the chi-square tests, it is found that the value of chi-square (χ^2) is 23.711, degree of freedom (df) is 20, and the p-value (p) to be 0.255 ($\chi^2(20) = 23.711$). The p-value is calculated by using the formula in Excel sheet (=CHISQ.DIST. RT (23.711, 20)) which is equal to .255 which is presented in APPENDIX C. The p-value calculated by the excel sheet is exactly the same as the p-value calculated by the chi-square test in Table 11. This p-value suggests that there is no sufficient evidence to prove that these two variables (safety training and the primary type of construction activities) are significantly associated. Concrete work, in particular, was associated with moderate to high levels of safety training, but framing and mechanical work were linked to low levels of safety training, as illustrated in Figure 22. Framing and mechanical work appeared to have a low degree of significance in terms of safety training, whereas electrical equipment work appeared to have a moderate to high level of significance. As seen in the bar graph, concrete work had a very high degree of significance with safety training in the moderate to high range, but other activities had insufficient evidence of significance with safety training. As a result, in this scenario, the researcher adopts the null hypothesis.

Table 12: Chi-square tests for the safety training and construction activities with most hazards

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)	Point Probability
Pearson Chi-Square	8.708[a]	24	.998	.991		
Likelihood Ratio	9.786	24	.995	.997		
Fisher-Freeman-Halton Exact Test	19.276			.936		
Linear-by-Linear Association	.029[b]	1	.865	.870	.446	.032
N of Valid Cases	129					

a. 30 cells (85.7%) have expected count less than 5. The minimum expected count is .02.

b. The standardized statistic is .170.

There were 129 valid participants who responded to this question. When chi-square tests were performed between the safety training and construction activities with most hazards, the value of chi-square $\chi^2(24)$ =8.708, degree of freedom (df) =24, and the p-value to be .998 which is shown in Table 12. The value chi-square is calculated in excel using (=CHISQ.DIST. RT (8.708, 24)), the p-value is .998. For the parameters specified in the value at which you want to evaluate the distribution and the degrees of freedom, the one-tailed probability of the chi-squared distribution is calculated. The Excel statistical function CHISQ.DIST.RT will determine the chi-square distribution's right-tailed probability. The observed and expected values are compared with this function and calculate the p-value.

In hypothesis testing, p-value is used to assist either accept or reject the null hypothesis. This p-value helps the researcher determine the variables' significance. The p-value provides the minimal level of significance at which the null hypothesis would be rejected as an alternative to rejection points. The p value serves as opposing evidence to the null hypothesis. The smaller is the p-value, the stronger the evidence that the researcher should reject the null hypothesis. The alternative hypothesis is more likely to be supported by stronger evidence when the p-value is lower. Statistical significance is typically defined as a p-value of 0.05 or less.

Table 13: Chi-square test for safety training & safety engineer or manager on site

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	31.848[a]	16	.010
Likelihood Ratio	27.973	16	.032
Linear-by-Linear Association	12.473	1	.000
N of Valid Cases	129		

a. 18 cells (72.0%) have expected count less than 5. The minimum expected count is .02.

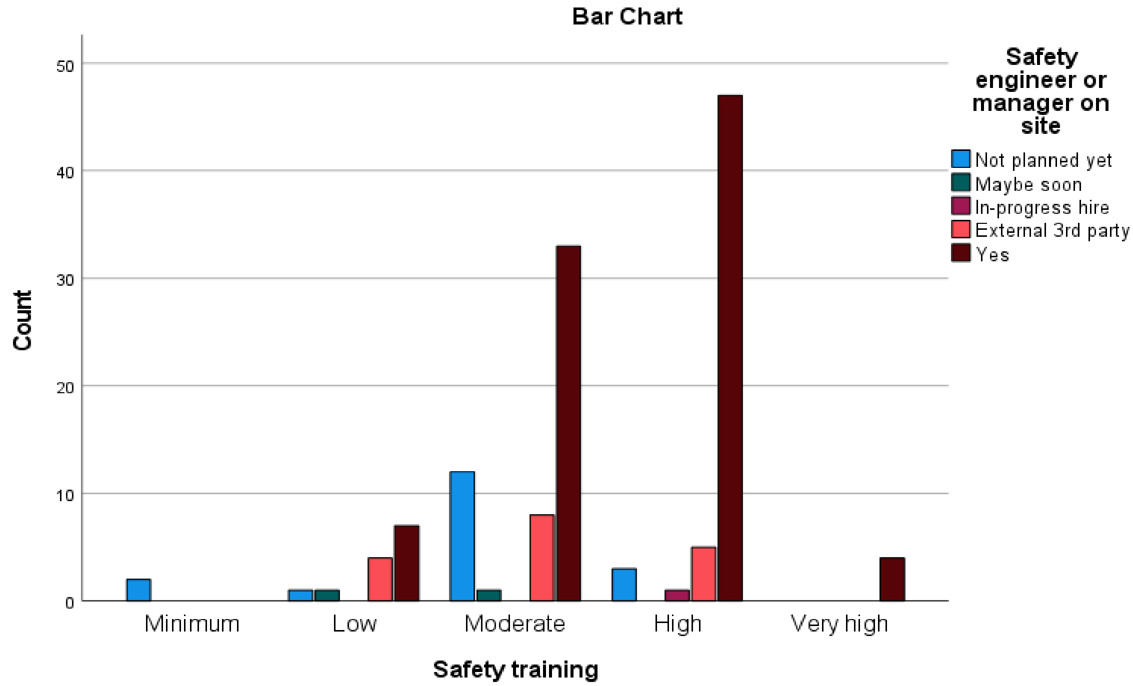


Figure 23: Bar graph of safety training with safety engineer or manager on site

Safety training was significantly associated with safety engineers or managers on-site, $\chi^2(16) = 31.848$, $p = .010$. More specifically, having either a safety engineer or manager on site was associated with moderate to high levels of safety training while planning for safety engineer or manager on site was associated with low level of safety training. 129 participants responded to this question. The chi-square result is shown in Table 13. Figure 23 shows that having a safety engineer or manager on site is associated with moderate to high level of safety training. However, there is a minimum correlation between safety training and not planning to have a safety engineer or safety manager on the site.

Table 14: Chi-square test for safety training & how do you approach if any hazards occur during the actual construction?

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	31.824[a]	16	.011
Likelihood Ratio	27.374	16	.038
Linear-by-Linear Association	9.628	1	.002
N of Valid Cases	128		

a. 17 cells (68.0%) have expected count less than 5. The minimum expected count is .17.

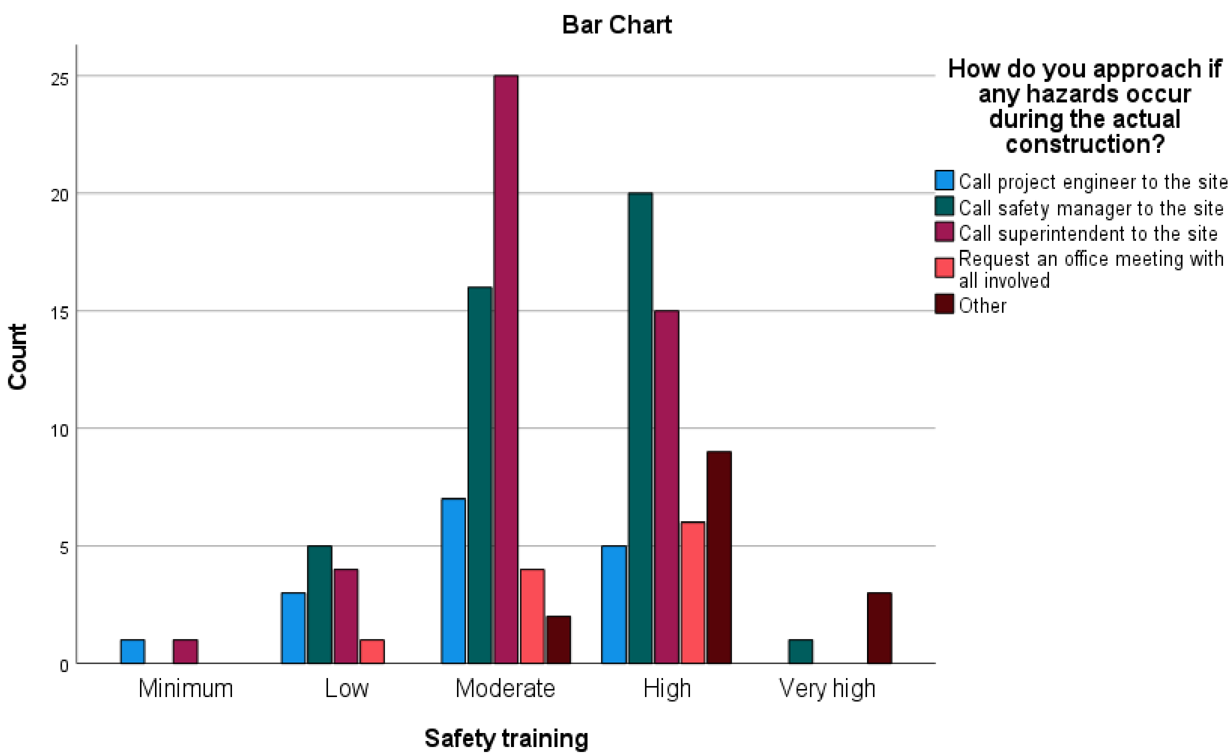


Figure 24: Bar graph of safety training with how do you approach safety hazards?

Safety training was significantly associated with safety engineers or managers on-site, $\chi^2(16) = 31.828$, $p = .011$. There were 128 participants in this survey question. More specifically, calling superintendent to site was associated with moderate to high levels of safety training, followed by calling safety managers to the site while calling project engineer to the site was associated with minimum level of safety training which is presented in Figure 24. The chi-square results are shown in Table 14.

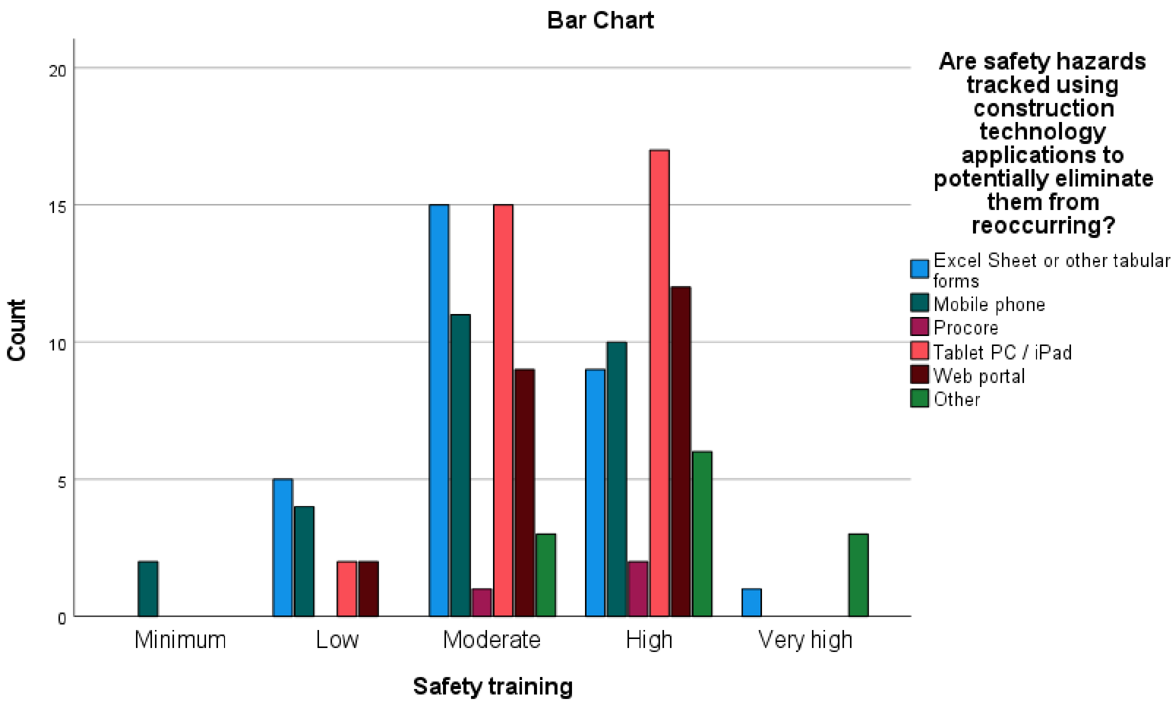


Figure 25: Bar chart of the safety training with technology used to track hazards

Safety training was significantly associated with tracking hazards using construction technology applications, $\chi^2(16) = 37.029$, $p = .012$ which is shown in Figure 25. Use of a tablet, PC, or iPad, a web portal, or a mobile phone application was indicative of higher levels of safety training. Tabular forms of tracking and methods falling into the ‘other’ category indicated very high levels of safety training while use of mobile phones accounted for minimum level of safety training.

Table 15: Chi-square tests for safety training & hazards during concrete activities

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	59.899[a]	28	.000
Likelihood Ratio	42.841	28	.036
Linear-by-Linear Association	4.085	1	.043
N of Valid Cases	114		

a. 34 cells (85.0%) have expected count less than 5. The minimum expected count is .02.

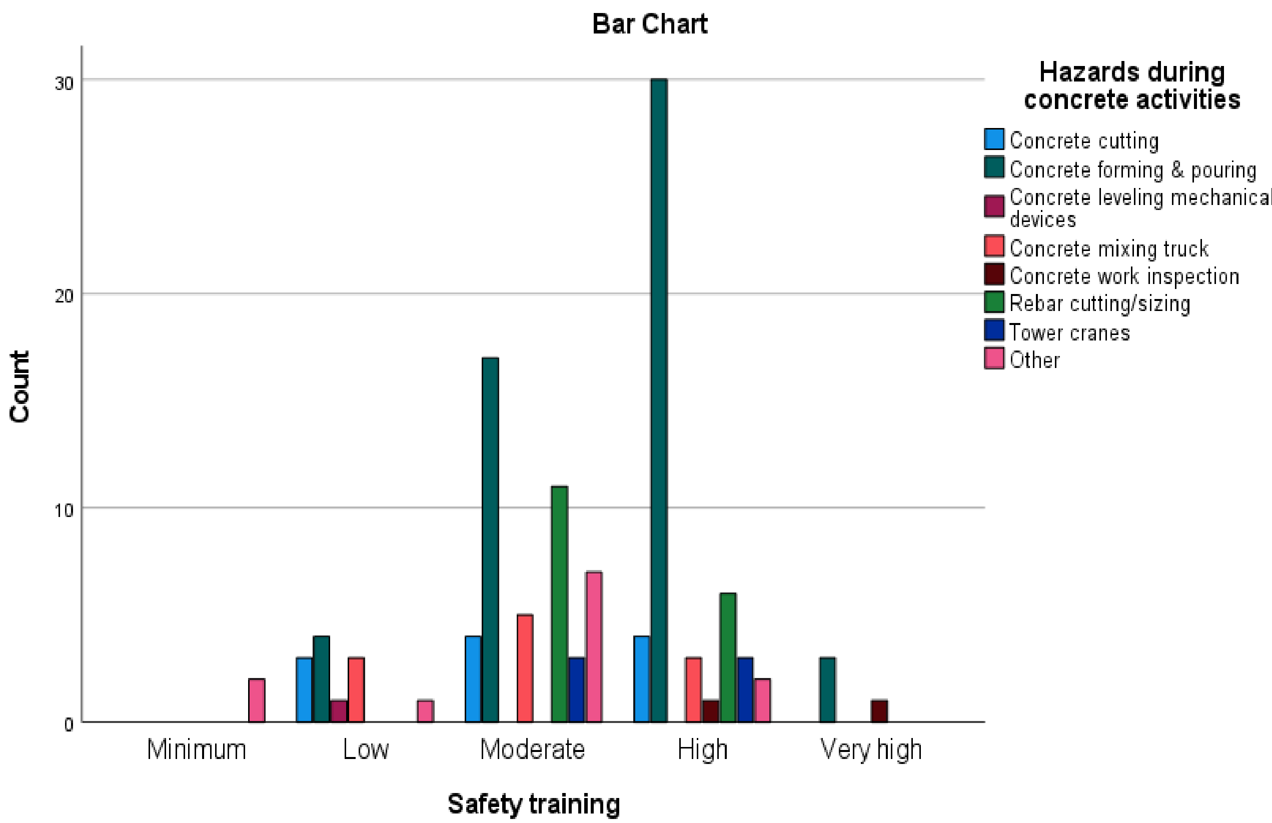


Figure 26: Bar chart of safety training with hazards during concrete activities

Safety training was also significantly associated with concrete activity-related hazards, $\chi^2(28) = 59.899$, $p < .001$. The chi-square results are shown in Table 15. There were 114 responses on this survey question. Concrete cutting, forming, pouring, and concrete mixing trucks were associated with lower levels of safety training, while forming and pouring and concrete work inspection was associated with very high levels which is shown in Figure 26.

Table 16: Chi-square tests for safety training & hazards during use of electrical equipment

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	29.612[a]	24	.198
Likelihood Ratio	32.588	24	.113
Linear-by-Linear Association	.085	1	.770
N of Valid Cases	119		

a. 25 cells (71.4%) have expected count less than 5. The minimum expected count is .05.

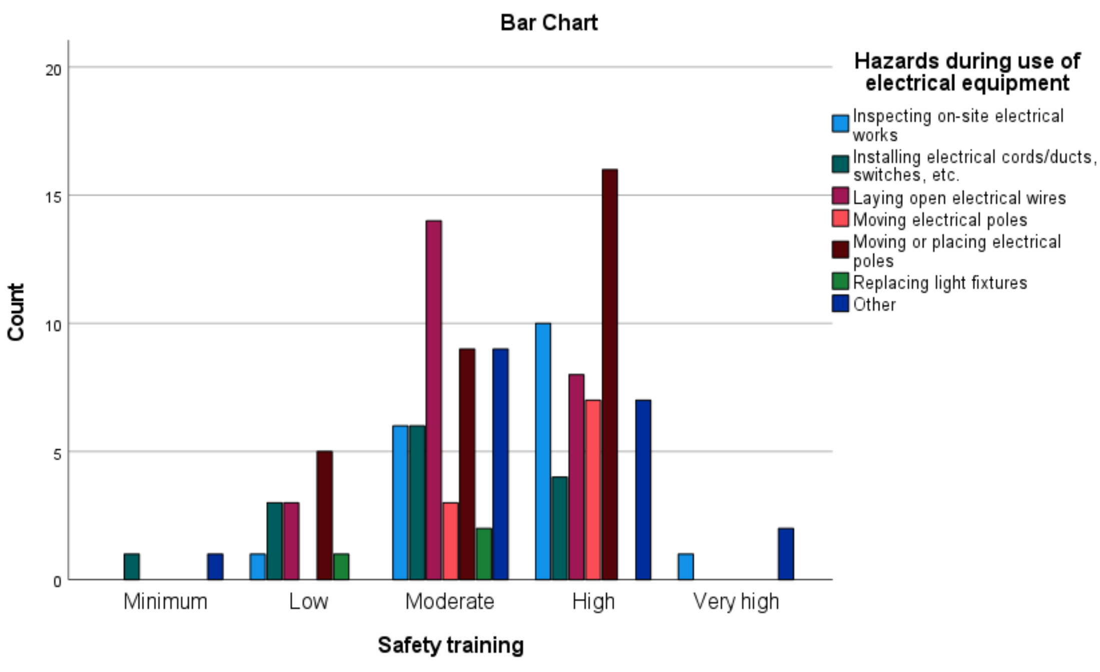


Figure 27: Bar chart of safety training with hazards during electrical equipment

Based on the results from chi-square tests, Safety training had no significant relationship with the hazards during the use of electrical equipment. Therefore, safety training was not associated with electrical equipment hazards, p > .05. $\chi^2(24) = 29.612$. The p-value is .198 which is greater than .05 shown in Table 16. There were 119 valid participants in this survey question. However, safety training was significantly associated with overall hazards related to construction activities, $\chi^2(28) = 58.469$, $p < .001$. Laying an open wire and moving or placing electrical poles were associated with moderate to high levels of safety training, while replacing the light fixtures were associated with minimum level of safety training which is shown in the Figure 27.

Table 17: Chi-square tests for safety training & hazards during operation of mechanical equipment

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	21.551[a]	20	.365
Likelihood Ratio	16.317	20	.697
Linear-by-Linear Association	.040	1	.842
N of Valid Cases	124		

a. 23 cells (76.7%) have expected count less than 5. The minimum expected count is .03.

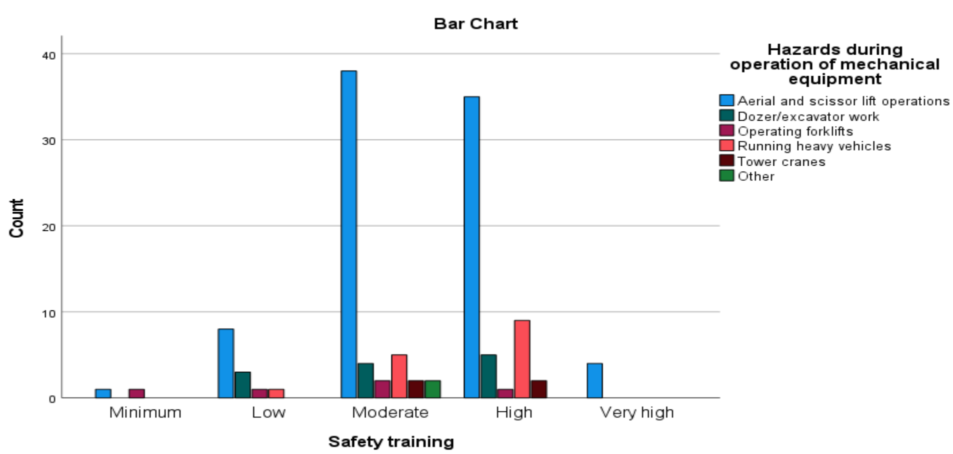


Figure 28: Bar graph of safety training with hazards during operation of mechanical equipment

The chi-square results suggest that there is no significant relationship between safety training and the hazards during the operation of mechanical equipment as the value of p is .365 which is greater than .05, $\chi^2(20) = 21.551$ which is presented in Table 17. There were 124 responses to this survey question. However, aerial and scissor lift operations have a moderate to high level of safety training, while dozer/excavator work and "others" have a minimum level of safety training which is presented in Figure 28. Safety training and plans for specific improvements were also significantly associated, $\chi^2(20) = 40.982$, $p = .004$. Very high levels of safety training were associated with providing incentives for specific safety goals, PPE, and tactics that fell into the 'other' category.

Table 18: Chi-square results for safety training & hazards during roofing activities

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	12.452[a]	20	.900
Likelihood Ratio	12.723	20	.889
Linear-by-Linear Association	2.220	1	.136
N of Valid Cases	115		

a. 21 cells (70.0%) have expected count less than 5. The minimum expected count is .12.

Based on the chi-square tests, safety training was not significantly associated with roofing activity-related hazards, $\chi^2(20) = 12.452$, $p=.900 > .05$. The chi-square result is shown in Table 18. There were 115 valid responses on this survey question. Installing trusses was associated with moderate to high levels of safety training while placing/removing shingles was associated with a minimum to moderate level of safety training and inspecting roof leaking had low to moderate level of safety training which is shown in Figure 29. Placing/removing shingles, inspecting roof leaks, and placing ceilings have a minimum level of significance with the level of safety training. There is not enough evidence to mention safety training is significantly associated with roofing activities besides only installing trusses.

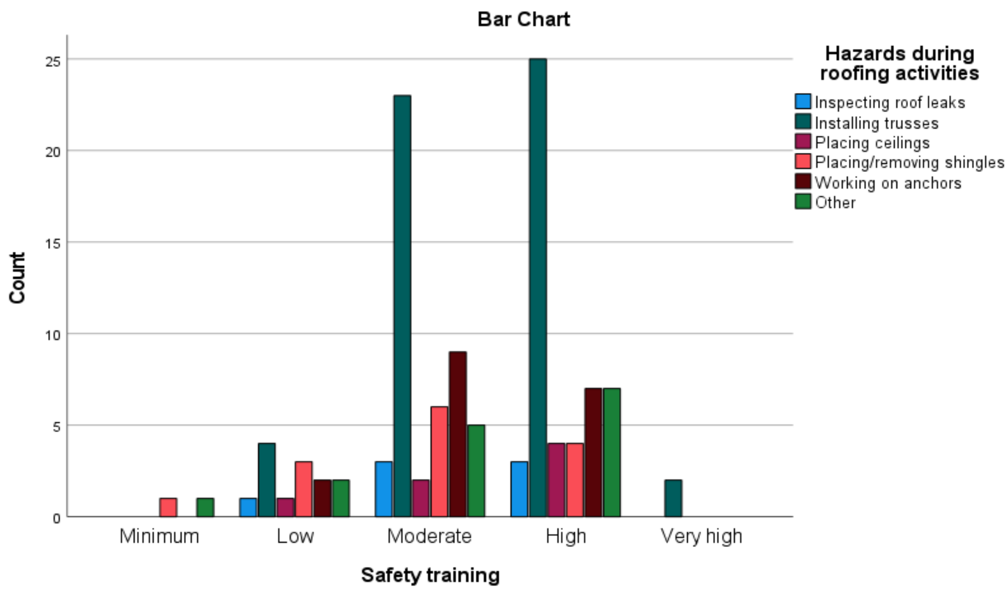


Figure 29: Bar graph of safety training with hazards during roofing activities

Technology Use/Advanced Device Training and Construction Activities

Technology use/advanced device training was not significantly associated with the primary type of construction activities, nor was it significantly associated with perceived risk of construction activities, $p > .05$. Also, Technology use/advanced device training was not significantly associated with having a safety engineer/manager on-site, method of approaching hazards, using construction technology, perceived hazards during construction activities, nor plans for specific improvements of safety hazards, $p > .05$.

Table 19: Observed & expected values for technology use and advanced device training with primary type of construction activities

Crosstab

			Primary type of construction activities						
			Concrete work	Electrical work	Framing	Mechanical work	Roofing activities	Other	Total
Technology use and advanced device training	Minimum	Count	21	3	4	5	2	9	44
		Expected Count	25.0	2.1	3.5	4.2	1.4	7.7	44.0
		% within Technology use and advanced device training	47.7%	6.8%	9.1%	11.4%	4.5%	20.5%	100.0%
		% within Primary type of construction activities	29.6%	50.0%	40.0%	41.7%	50.0%	40.9%	35.2%
		% of Total	16.8%	2.4%	3.2%	4.0%	1.6%	7.2%	35.2%
	Low	Count	22	3	2	4	0	9	40
		Expected Count	22.7	1.9	3.2	3.8	1.3	7.0	40.0
		% within Technology use and advanced device training	55.0%	7.5%	5.0%	10.0%	0.0%	22.5%	100.0%
		% within Primary type of construction activities	31.0%	50.0%	20.0%	33.3%	0.0%	40.9%	32.0%
		% of Total	17.6%	2.4%	1.6%	3.2%	0.0%	7.2%	32.0%
	Moderate	Count	24	0	3	3	0	3	33
		Expected Count	18.7	1.6	2.6	3.2	1.1	5.8	33.0
		% within Technology use and advanced device training	72.7%	0.0%	9.1%	9.1%	0.0%	9.1%	100.0%
		% within Primary type of construction activities	33.8%	0.0%	30.0%	25.0%	0.0%	13.6%	26.4%
		% of Total	19.2%	0.0%	2.4%	2.4%	0.0%	2.4%	26.4%
	High	Count	3	0	1	0	2	1	7
		Expected Count	4.0	.3	.6	.7	.2	1.2	7.0
		% within Technology use and advanced device training	42.9%	0.0%	14.3%	0.0%	28.6%	14.3%	100.0%
		% within Primary type of construction activities	4.2%	0.0%	10.0%	0.0%	50.0%	4.5%	5.6%
		% of Total	2.4%	0.0%	0.8%	0.0%	1.6%	0.8%	5.6%
	Very high	Count	1	0	0	0	0	0	1
		Expected Count	.6	.0	.1	.1	.0	.2	1.0
		% within Technology use and advanced device training	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%
		% within Primary type of construction activities	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%
		% of Total	0.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%
Total		Count	71	6	10	12	4	22	125
		Expected Count	71.0	6.0	10.0	12.0	4.0	22.0	125.0
		% within Technology use and advanced device training	56.8%	4.8%	8.0%	9.6%	3.2%	17.6%	100.0%
		% within Primary type of construction activities	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	56.8%	4.8%	8.0%	9.6%	3.2%	17.6%	100.0%

Table 20: Chi-square results for Technology Use/Advanced Device Training and Construction Activities

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	26.592[a]	20	.147
Likelihood Ratio	23.025	20	.288
Linear-by-Linear Association	1.765	1	.184
N of Valid Cases	125		

a. 24 cells (80.0%) have expected count less than 5. The minimum expected count is .03.

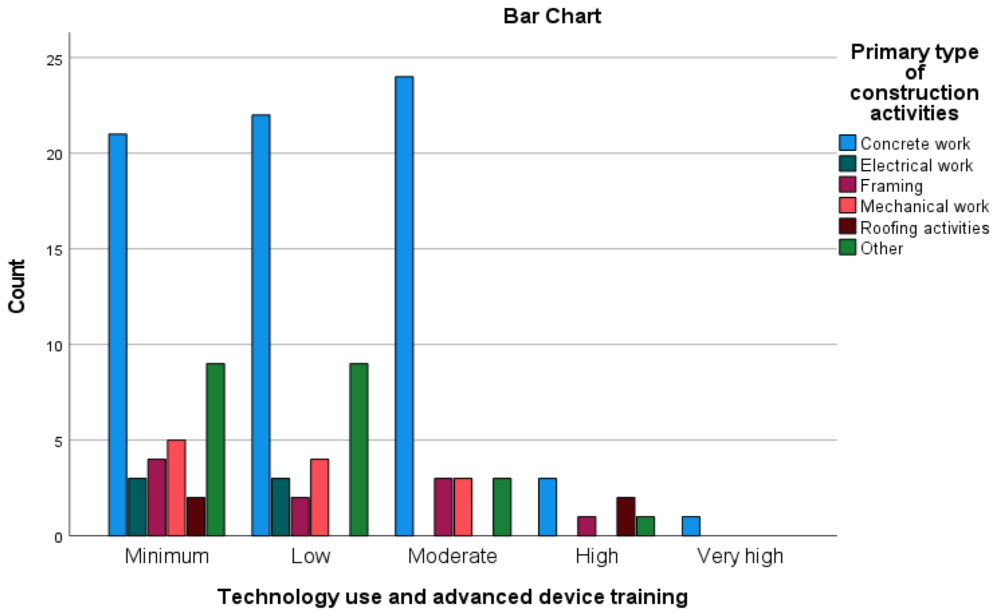


Figure 30: Bar graph of Technology Use/Advanced Device Training with primary type of construction activities

The observed and the expected values of technology use and advanced device training is shown in Table 19. These values are used to calculate the chi-square tests. Again, framing and "other" types of building operations were included in the question to provide respondents some flexibility. The analysis does not include the two construction activities mentioned above. Based on the chi-square tests, technology use and advanced device training was not significantly associated with primary type of construction activities as, $\chi^2(20) = 26.592$, p=.147 > .05.

The chi-square results are shown in Table 20. There were 125 valid responses on this survey question. Concrete work had minimum to moderate level of technology use and advanced device training while mechanical work had low to moderate level of technology use and advanced device training which is shown in Figure 30.

Table 21: Chi-square test for overall perceived safety performance and the primary type of construction activities

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	33.229[a]	20	.032
Likelihood Ratio	32.655	20	.037
Linear-by-Linear Association	.143	1	.706
N of Valid Cases	125		

a. 24 cells (80.0%) have expected count less than 5. The minimum expected count is .03.

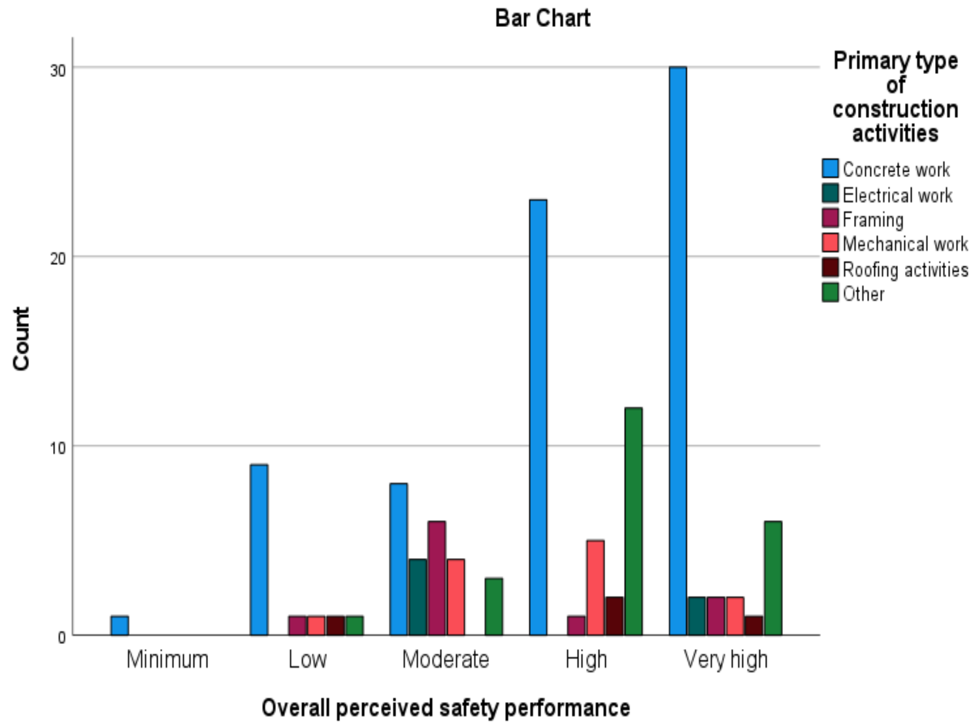


Figure 31: Bar graph of overall perceived safety performance with primary type of construction activities

There was a significant association between overall perceived safety performance and primary types of construction activities, $\chi^2(20) = 33.229$, $p = .032$ which is shown in Table 21. Based on the survey findings, concrete work was associated with very high perceived safety performance while framing work was associated with low perceived safety performance which is presented in the Figure 31. Perceived safety performance was not associated with approaches used during construction for any hazards, $p > .05$. However, overall perceived safety performance was not significantly associated with construction activities with the most hazards, as per the participants, $p > .05$. Overall safety performance was significantly associated with safety engineers/managers on-site, $\chi^2(16) = 34.375$, $p = .005$. Higher high safety performance was indicative of those with safety engineers/managers on site.

Table 22: Chi-square test for overall perceived safety performance and construction activities with the most hazards

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-Square	17.864[a]	24	.810
Likelihood Ratio	22.618	24	.542
Linear-by-Linear Association	.122	1	.726
N of Valid Cases	125		

a. 29 cells (82.9%) have expected count less than 5. The minimum expected count is .01.

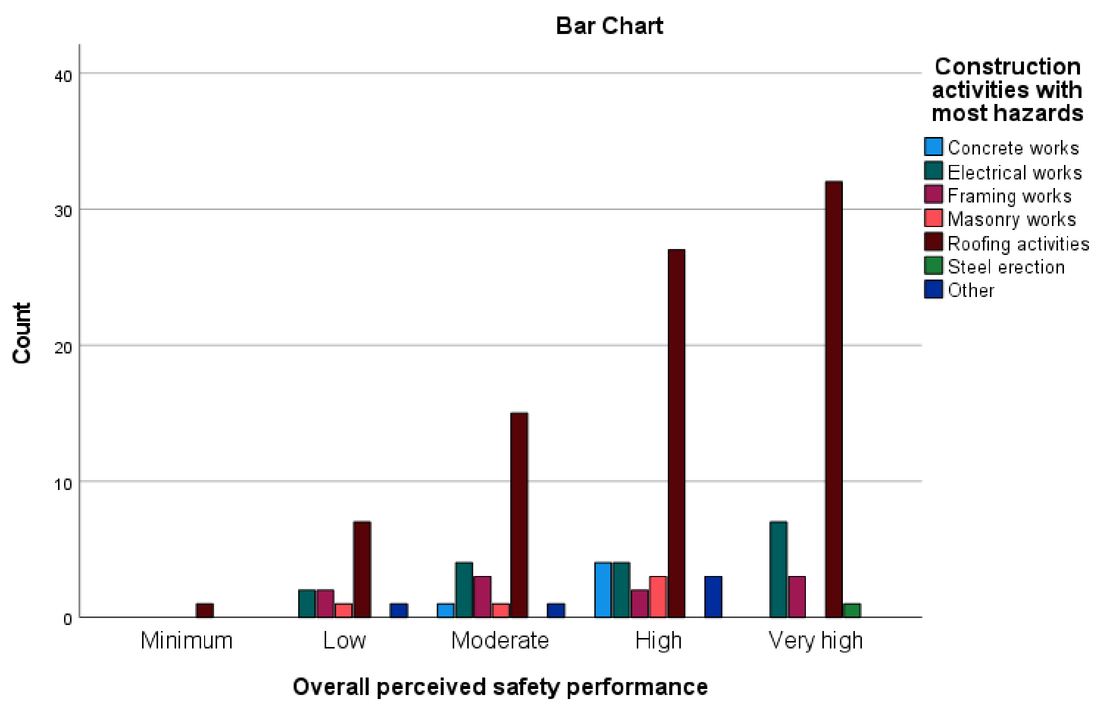


Figure 32: Bar graph of overall perceived safety performance and construction activities with the most hazards

Based on the findings, overall perceived safety performance was not significantly associated with concrete activities, electrical activities, hazards during operation of mechanical equipment, roofing activities, overall construction activities, nor was it associated with plans for specific improvements of safety hazards as, $p > .05$. The chi-square tests $\chi^2(24) = 17.864$, $p = .810 > .05$ which is presented in the Table 22. Roofing works accounted for high to very high levels of perceived safety performance while electrical works were associated with low to moderate overall safety performance which is shown in the Figure 32. However, overall perceived safety performance was associated with using technology applications for safety hazards, $\chi^2(20) = 33.668$, $p = .028$.

Qualtrics Survey Responses

To some extent, the Qualtrics survey responses associated with construction professionals and companies' demographics have been described in the data analysis section. In addition, in the previous chapter, questions about safety training, technology use, and overall perceived safety performance were discussed. Also, three questions derived from qualitative data were addressed in Chapter 4 above (Analysis of Qualitative Data). The remainder of the Qualtrics survey questions are included below in no particular sequence. The following material is provided to help the audience comprehend the research questions.

What are the sources of hazards occurring in your construction activities? (Select all that apply)

Based on the survey results in Figure 33, 17.85% (n= 86) were related to hazards due to ladders, 15.53 % (n=82) weather conditions, 15.53% (n=75) were related to the Mechanical/Electrical equipment while 13.98% (n=67) of the hazards were due to aerial and scissor lifts, open slabs account for 9.73% (n=47), and the least 2.37% (n=11) were other sources. The bar graph shows the sources of hazards occurring during construction activities.

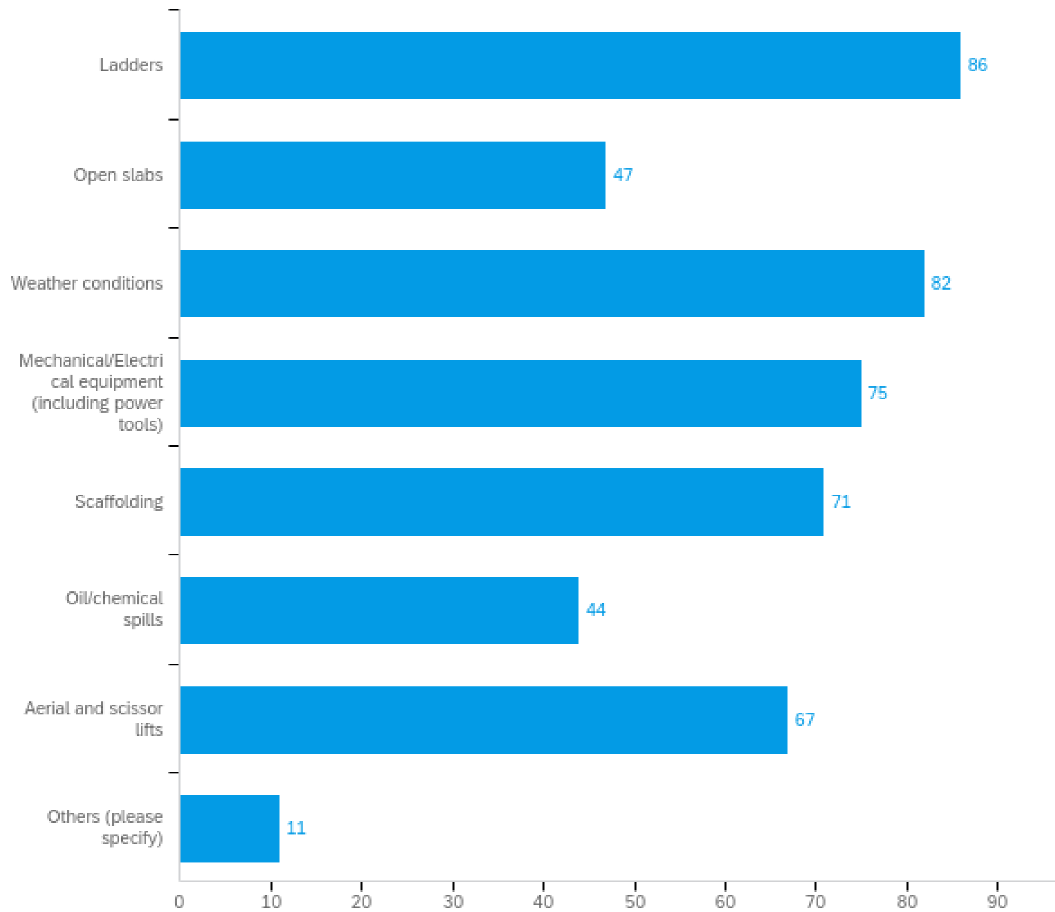


Figure 33: Survey results (source of hazards)

Are safety hazards tracked using construction technology applications to potentially eliminate them from reoccurring? (Choices of devices/forms used)

From the survey results, 26.87% (n= 36) accounted for tablet PC / iPad use to track safety hazards, followed by 23.13% (n=31) using Excel sheets, mobile phone accounts for 21. 74% (n=30), web portal with 18.84% (n=26), and lastly, 11.19% (n=15) using other technology means. The Figure 34 shows the results of construction technology used from survey questions.

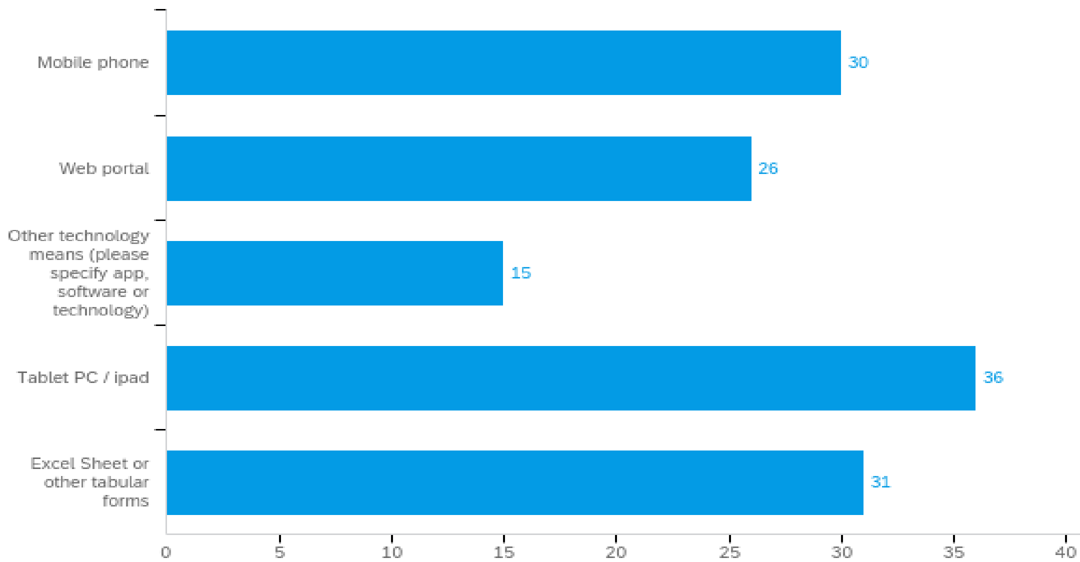


Figure 34: Survey results (construction technology used)

Does your company involve a BIM person within the VDC Department for safety-related matters?

Based on the survey results, 40.32% (n=52) mentioned that their company uses a BIM dedicated person, followed by 38.71% (n=48) mentioned that their company has not planned yet to have a BIM person in the house, 10.94 % (n=14) mentioned planning soon, and lastly, 4.03% (n=5) mentioned they are in the process of hiring BIM dedicated person. The Figure 35 shows the results of the survey.

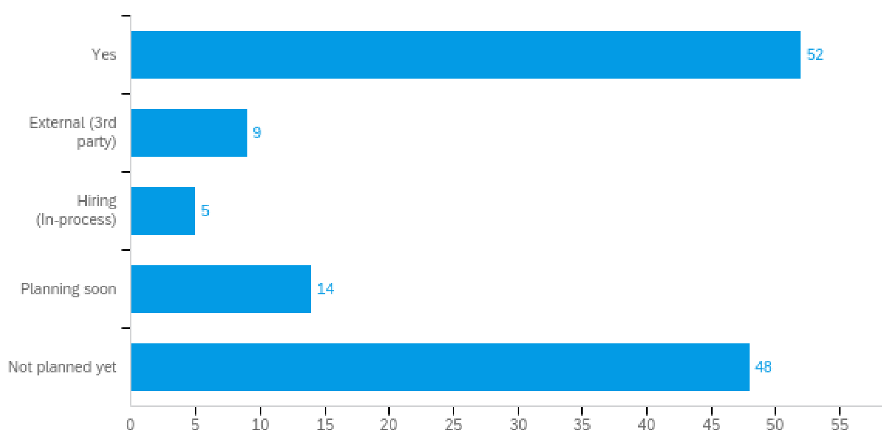


Figure 35: Survey results (Has BIM person in the company)

In your opinion, what is the probability of identifying hazards during your projects' design phase?

From the survey results in Figure 36, 40.32% (n=52) mentioned the probability of identifying hazards during the project's design phase is on average (40-60%), while 35% (n=32) mentioned high, 15.63% (n=20) mentioned the probability of identifying hazards is low (20-40%), and the least 7.26% mentioned the probability is very high during the design phase.

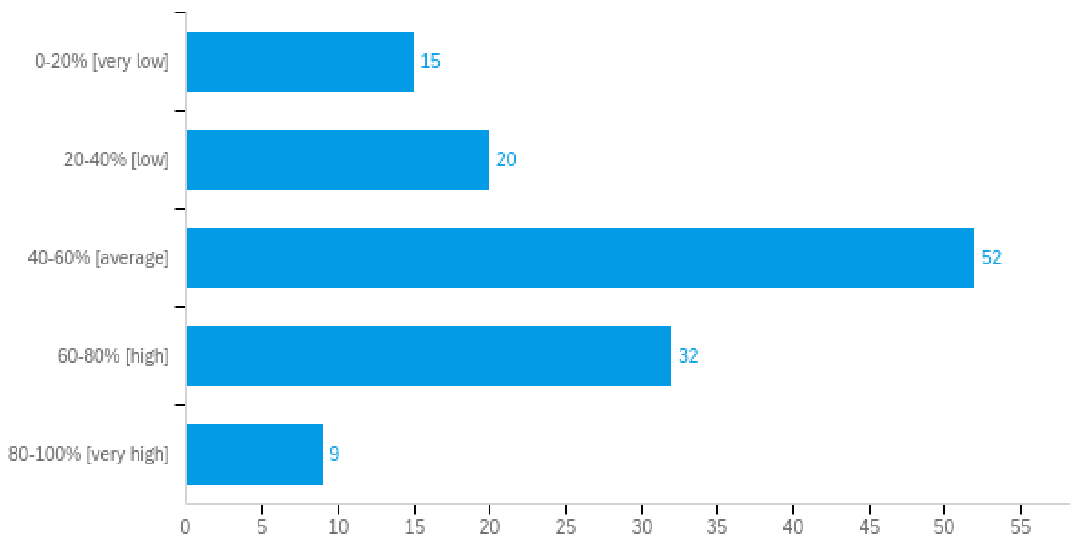


Figure 36: Survey results (Probability of identifying hazards)

Does your company use virtual/augmented reality devices for employee safety training in the virtual environment?

The survey results found that 41.41% (n=53) never use VR/AR devices for safety training, while 24.19% (n=33) mentioned they use them sometimes, 20.31% (n=26) mentioned they use VR/AR rarely, and the least 4.03% (n=5) mentioned their company always uses VR for safety training. The bar graph in Figure 37 shows the responses for the use of VR for safety training.

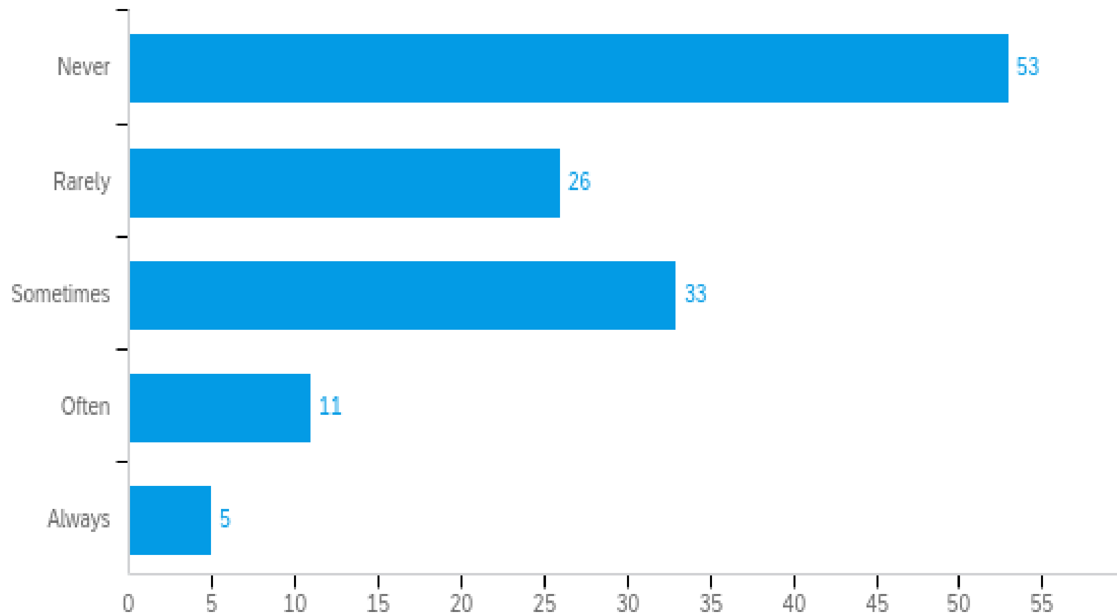


Figure 37: Survey results (Use of VR for safety training)

Does your company implement Virtual, Augmented, or Mixed Reality (VR/AR/MR) to identify possible design errors and a better approach to safety hazards?

Based on the survey findings, 42.52% (n=54) mentioned they implement VR/AR/MR to identify possible design errors and approach safety hazards, followed by 25.20% (n=32) saying they implement sometimes, and lastly, 15.75% (n=20) mentioned rarely, and only 3.25% (n=4) saying they implement VR devices consistently. The bar graph of implementing VR to identify possible hazards is shown in Figure 38.

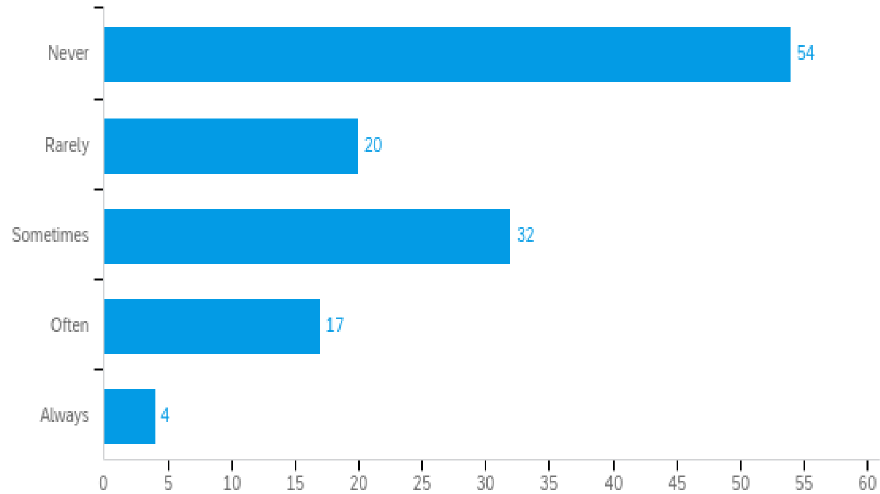


Figure 38: Survey results (Use of VR/AR/MR to identify possible design errors)

Has your company integrated 3D BIM models in conjunction with VR/AR/MR devices for design and construction safety purposes?

The survey results found that 39.84% (n=51) responded that their company did not integrate BIM and VR devices for design and safety purposes, while 31.25% (n=40) mentioned sometimes, 15.63% (n=20) mentioned rarely, and surprisingly the least 0.81%(n=1) mentioned almost always. The bar chart below in Figure 39 shows the results of BIM and VR devices integration from the survey.

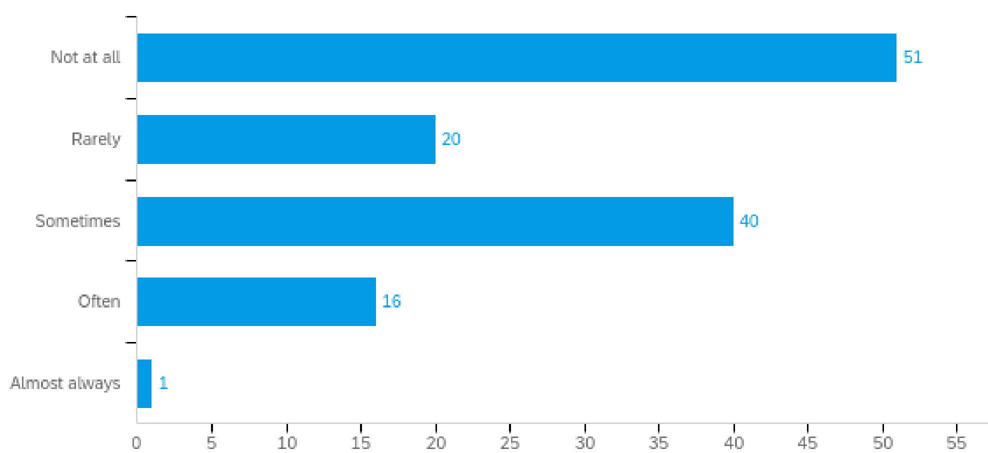


Figure 39: Survey results (Use of 3D BIM and VR/AR/MR for safety purposes)

Does your company integrate 3D BIM models and VR/AR/MR devices to approach safety hazards in a virtual laboratory/site?

Based on the survey findings, 44.09% (n=56) mentioned their company does not integrate 3D BIM models and VR devices at all to approach safety hazards in the virtual lab, while 24.41% (n=31) mentioned they use it sometimes, 17.32% (n=22) of the participants mentioned rarely, and the least of 3.25% (n=4) always integrate BIM and VR for safety identification. The bar chart below in Figure 40 shows the percentage of the company integrating BIM and VR devices for hazard identification.

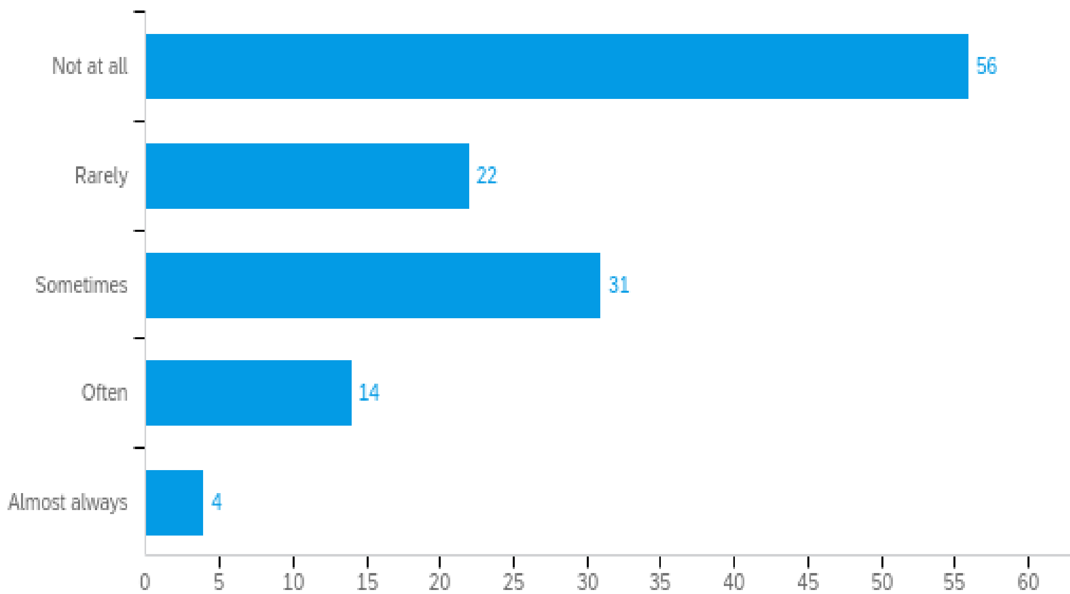


Figure 40: Survey results (Integrating 3D BIM and VR/AR/MR to approach hazards)

Please identify an approximate average percentage of the real hazards present per project in your company after integrating 3D BIM models with VR/AR devices:

The results found that 59.06% (n=75) mentioned they could not estimate the findings of real hazards present per project in their company, while 20.74% (n=26) mentioned an average finding (40-60%), 10.24% (n=13) of the participants mentioned a very low range (0-20%), and the least around 0.79% (n=1) of the company identified natural hazards per project while integrating 3D BIM and VR devices. The response from the survey is presented in Figure 41 below on a bar graph.

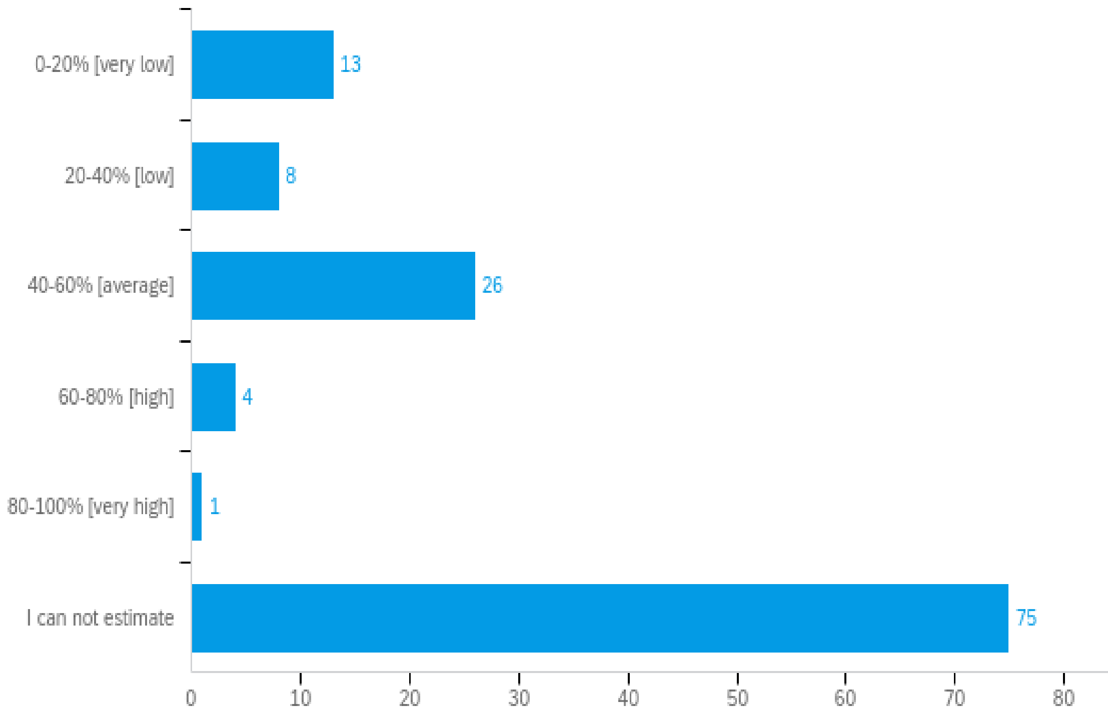


Figure 41: Survey results (Percentage of hazards identified)

Are the Virtual Reality tools (if used) helpful for identifying, minimizing, and sometimes eliminating hazards in your company?

The survey results in Figure 42, showed that 43.80% (n=53) of the responders were neutral when asked if VR devices helped identify, minimize, and sometimes eliminate safety hazards by their company, while 38.84% (n=47) of the participants agree that VR tools are helpful in identifying, minimizing, or eliminating hazards, 14.05% (n=17) mentioned they strongly agreed that it was helpful, and the least 1.65% (n=2) mentioned they strongly disagree that BIM and VR helped in hazard identification and minimization.

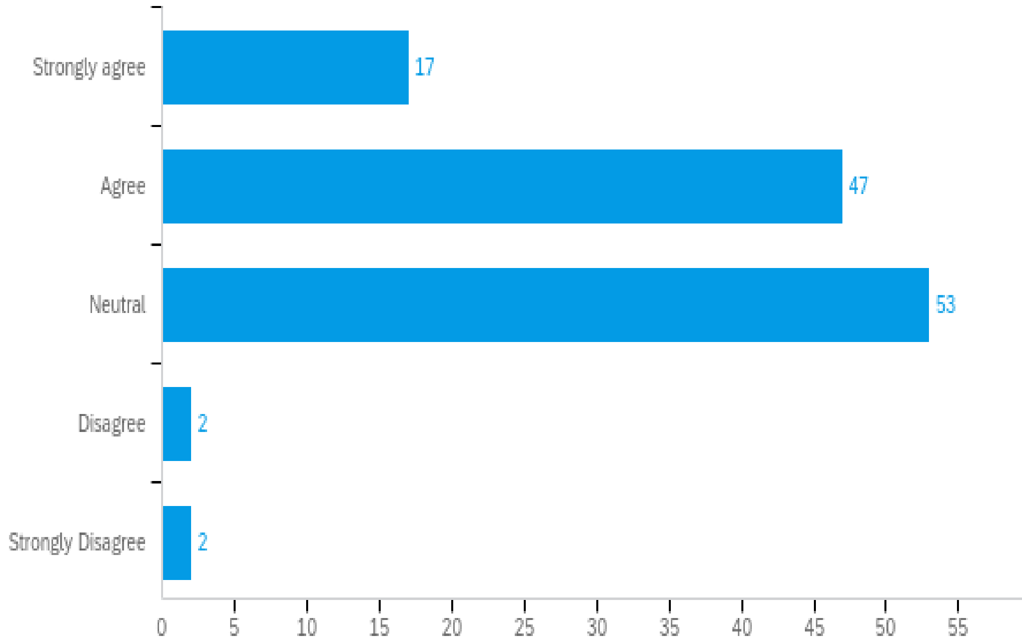


Figure 42: Survey results (Were VR tools helpful?)

In your opinion, what is the overall perceived safety performance at your company for construction professionals?

The survey results showed that 35.66% (n=46) of the responders mentioned the overall perceived safety performance at their company was good, while 33.33% (n=43) mentioned an excellent performance, 10.40% (n=13) were a satisfactory performance, and the least 0.80% (n=1) encountered a poor performance at their company. Figure 43 represents the overall perceived safety performance from the Qualtrics survey.

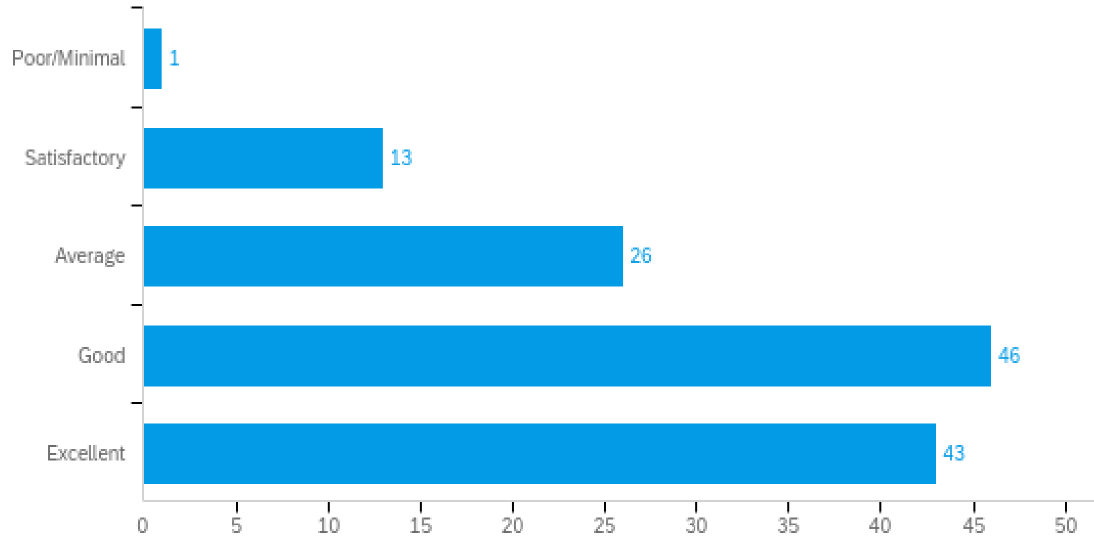


Figure 43: Survey results (Overall perceived safety performance)

Does the company have plans for specific improvements to promote and minimize these safety hazards?

Based on the survey findings in Figure 44, 37.50% (n=51) of the responders mentioned providing safety training more often as a specific improvement to promote and minimize safety-related hazards. In comparison, 27.21 % (n=37) mentioned performing more safety awareness programs, 12.50% (n=17) mentioned providing incentives for specific safety goals, 10.29% (n=14) mentioned to hire more safety professionals, and the least 5.88% (n=8) of the responders mentioned using more safety-related technologies as a specific goal to promote and minimize any construction-related hazards.

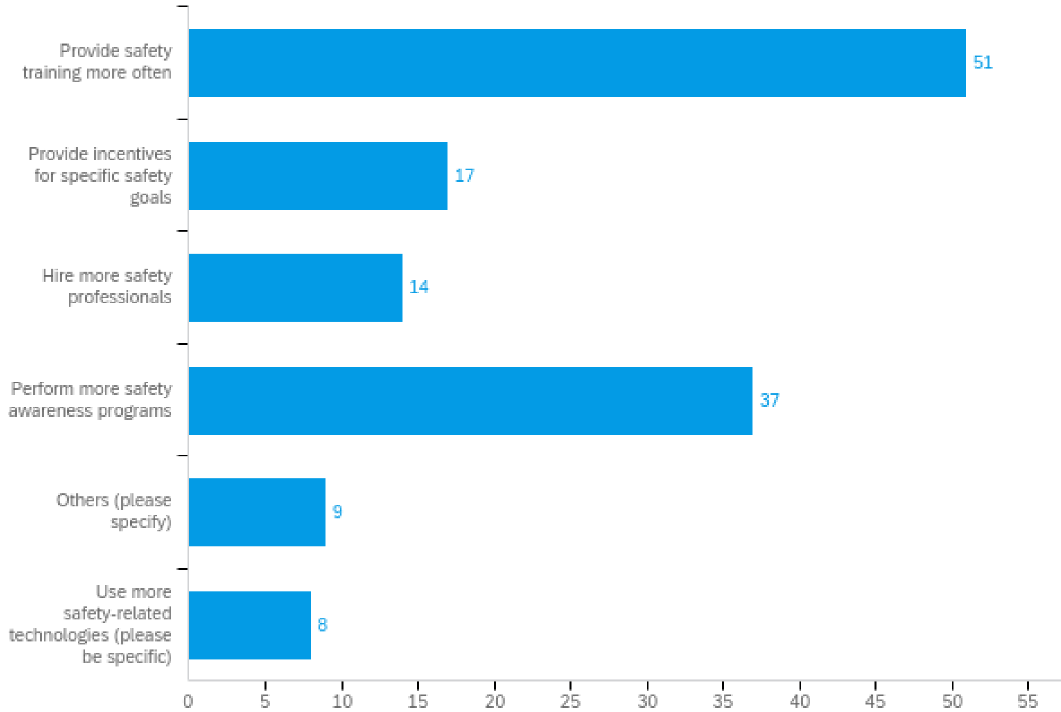


Figure 44: Survey results (Specific plans to improve further?)

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusion and Recommendations for further research

The primary purpose of this research was to determine the relationship between BIM and VR devices to identify and minimize the impact of hazards in certain major construction activities. The outcomes of this study should enable the construction practitioners such as project managers, construction managers, engineers, architects, contractors, subcontractors, and superintendents to provide an opportunity to offer better safety training and foresee the construction operations in the virtual environment, reducing the hazards during the actual project execution. The findings and suggestions could also be used to improve course design for students by researchers looking at the impact of BIM and VR on construction safety and hazard mitigation. This chapter presents the outcomes, the conclusion, and recommendations for further studies based on the quantitative and qualitative results. The study hypothesized that implementing BIM and VR devices in pre-construction of most projects would identify and reduce hazards significantly, eliminate incidents/accidents from construction operations, and enhance safer projects. The main conclusions were drawn from the resulting quantitative and qualitative analysis presented in the previous chapter.

Over the last decade, researchers worldwide have used VR, AR, and MR technologies for numerous safety-related applications such as pre-construction design and safety planning, construction hazard monitoring, safety hazard identification, and safety training. The most common hazards identified in the construction industry were falls from the heights, slab openings, staircase work, roof work, and other general safety hazards. Combining VR, AR, and MR with 3D BIM models is useful in hazard detection for the construction industry. The common goals of VR, AR, and MR applications in the construction industry are safety and training, so researchers worldwide have used these technologies to develop hazard detection skills, hazard awareness, and communication to mitigate hazards (Moore and Gheisari, 2019). Fard et al. propose developing 4D environments that include audio effects to 3D environments, which could significantly increase the virtual simulation of construction projects while also lowering the risk of accidents in the construction industry (Fard et al., 2011). Hazard detection and minimization may also be achieved by highly qualified safety training in an immersive simulated environment or a real-world location.

This research presents conclusions based on real-world data. The case studies have been meticulously categorized to find the industry's most prevalent dangerous construction activities. Based on the case studies, a questionnaire was constructed. Frequently occurring hazardous workplace scenarios are discussed with a group of industry specialists. This data offered the researcher a notion of industrial viewpoints, and the researcher conducted statistical analysis to study the data and identify the facts. In addition, the researcher evaluated and integrated various hazardous scenarios within the VR devices. As a result, case studies have been developed, professional replies have been examined for facts, and models have been tested to make this study more applied. The study hypothesized that combining BIM into VR devices in construction projects would result in a considerable increase in the detection of construction-related risks and hazards, potential to their elimination, and as a result, identification of hazardous situations leading to less accidents. The quantitative and qualitative analyses reported in the preceding chapter (chapters 4.3 and 4.4) were used to report on the findings. According to the findings, 48.9% of the survey participants used BIM and VR devices combined in their work system. When asked if they believed BIM might play a significant role in hazard detection and mitigation, 48.9% replied yes, 22.8 percent said no, and 28.3 percent stated they did not know. The chi-square test was used to examine the variability of the independent factors' hazard recognition performance when they were crossed with the dependent variables (i.e., safety training, technology usage/advanced device training) to test the alternative hypothesis. Safety training had an evidence of significant relationship with the concrete activities while the other sub-activities within the roofing, electrical equipment, and the mechanical equipment works had some level of significance. However, sub-activities within these three activities (roofing, electrical equipment, and the mechanical equipment works) had a strong evidence of significance. For instance, laying open electrical wires and moving or placing electrical poles have a strong evidence of significance within the electrical equipment works. In addition, inspecting on-site electrical works has a high level of significance with the safety training. During operation of mechanical equipment, aerial and scissor lift operations, working on anchors, and placing/removing shingles also have a moderate to high level of safety training. This states that there is strong evidence of significance among these two variables.

Safety training is significantly associated with a moderate to high level of safety engineer or manager having on the site. In addition, calling the superintendent and safety manager to the site have strong evidence of significance with the safety training. Also, safety training was significantly associated with tracking hazards using construction technology applications, $\chi^2(16) = 37.029$, $p = .012$. Use of a tablet, PC, or iPad, a web portal, or mobile phone application was indicative to higher levels of safety training. Tabular forms of tracking and methods falling into the 'other' category were indicative of very high levels of safety training. Again, safety training was also significantly associated with concrete activity-related hazards, $\chi^2(28) = 59.899$, $p < .001$. Concrete cutting, forming, pouring, and concrete mixing trucks were associated with lower levels of safety training while forming and pouring as well as concrete work inspection was associated with very high levels. The data indicate that safety training was not significantly associated with electrical equipment hazards, mechanical equipment, or roofing activities, p > .05. However, safety training was significantly associated with overall hazards related to construction activities, $\chi^2(28) = 58.469$, $p < .001$. Ladders, open slabs, mechanical/electrical equipment, weather conditions, and oil/chemical spills were associated with high levels of safety training. Lastly, safety training and plans for specific improvements were also significantly associated, $\chi^2(20) = 40.982$, $p = .004$. Very high levels of safety training were associated with providing incentives for specific safety goals, PPE, and tactics that fell into the 'other' category.

The use of technology and advanced device training to mitigate safety concerns was associated with a high to very high level of perceived safety performance, $\chi^2(20) = 33.668$, $p = 0.028$. There was a significant association between overall perceived safety performance and primary types of construction activities, $\chi^2(20) = 33.229$, $p = .032$. Also, concrete work was associated with very high perceived safety performance. In addition, overall safety performance was significantly associated with safety engineers/manager on site, $\chi^2(16) = 34.375$, $p = .005$. Higher safety performance was indicative of those with safety engineers/managers on site. The overall perceived safety performance was also significantly associated with the roofing work while concrete work had a minimum level of significance. There are significant associations among the sub-activities and do provide strong evidence of association. Based on the findings, concrete works have a strong evidence of significance with the safety training, use of technology and advanced device training to mitigate safety hazards, and the overall perceived safety performance. Perceived safety performance was associated with the use of technology applications for safety hazards, $\chi^2(20) = 33.668$, $p = .028$. However, roofing, mechanical equipment, and the electrical equipment works have some levels of significance with the dependent variables but do not provide strong evidence to accept the alternative hypothesis.

The results of the overall quantitative findings are used to test the alternative hypothesis. To determine if the alternative hypothesis is acceptable, multiple chi-square tests were performed between the dependent variables and the independent variables. The results revealed that some of the construction activities had a very high level of significance among the variables while few had a minimum level of association. The sub-activities within the four case studies had a strong level of significance with one or the other dependent variables. The data indicated that there are significant findings concerning technology applied to projects in this study. However, this correlation among the sub-activities and minimum significance within the major construction activities would possibly lead to accepting the null hypothesis for this research. Indeed, through qualitative and quantitative inquiries, this research gave a chance to better understand the sources of hazards on certain construction activities and, as a result, provide evidence toward minimizing safety hazards.

According to some participants, BIM played a critical role in hazard detection. Some participants believe it aids in detecting potential failures and that it is particularly useful in risk management because of its capacity to record every detail required in the construction of a project, even down to the details level. Those that do not employ BIM, on the other hand, claim to examine project plans and other helpful imagery before and during the building phase to identify possible areas of safety-related weakness. Others argue that expertise and care should be employed instead of BIM. While numerous people mentioned the benefits of BIM, they were reporting that they do not currently utilize it.

The findings of this study showed that the VR-based safety training program is far more effective. To emphasize accident causation and the significance of detailed hazard recognition and appropriate risk perception, researchers created a training technique that simulated appropriate actions for behaviors in close proximity with identified hazards into a VR environment. The researchers were able to identify more hazards in the lab after training, perceive them as having a higher level of risk, and utilize appropriate management measures to mitigate the risks, suggesting that virtual reality settings give a high level of realism, which enhances training outcomes. However, this sort of training is needed to put into tests with the actual construction workers and other industry professionals.

A mixed-method approach was employed, including qualitative and quantitative analytic methods. As for the survey, a set of 30 questions was created. From civil or construction engineering and management students to project managers, also a larger group of construction professionals participated in the survey. Lastly, four case studies with the most dangerous situations of their construction areas were developed (their respective 3D virtual models) based on the data gathered from OSHA and independent industry companies from the US-SE region. The outcomes of this study should enable the construction practitioners such as project managers, construction managers, engineers, architects, contractors, subcontractors, and superintendents to provide safety training and foresee fluidly the construction operations in the virtual environment, having the potential of reducing the hazards and their impact during the actual project execution. This research provides information on how virtual, augmented, and mixed reality tools and techniques might be utilized to identify and mitigate hazards, as well as for safety education. However, this study focuses solely on virtual reality and 3D BIM. Only in the body of the literature review is the AR and MR thoroughly discussed. In this research, the 3D BIM models are simulated in a VR environment employing only a VR device (Oculus Quest 2). The case studies that were created were based on current issues. The researchers believe that this work will help the audience think of ways to improve safety on the jobsite thru the virtual world. This paper depicts the VR process. As a consequence, a similar method might be utilized to detect hazards in the same construction activities as in this study or in different construction activities depending on the frequent hazard's occurrence. In addition, this research experimentation covers VR walkthroughs in depth, including how safety issues may be recognized and potentially mitigated to avoid incidents/accidents by showing avatars in red color coded which makes audience visible. Finally, the VR integration with 3D models technology might be employed in construction safety classes for educational purposes as well as safety training in multiple construction companies.

Research Limitations relative to the study set-up and results interpretations

The main focus of this research was the compounded effect of BIM and VR devices on identifying and eliminating construction safety hazards as much as possible by using the technology. The designated survey applied to industry professionals aimed to examine whether adopting BIM, VR, AR devices together have an effect on major construction hazards identification and impact minimization. The results of this survey could be helpful to the construction practitioners in the industry to improve project execution practice by improving hazardous scenarios recognition and establishing safety practices before the actual real-life production. The study shows that VR usage, also (AR and MR) technologies improve the efficiency of hazard detection and mitigation in the major construction activities. Nonetheless, there are some research limitations to this endeavor. This study was conducted within surrounding Georgia, including the state of Georgia. The small size sample of data is insufficient to show that the 3D BIM and VR technology works flawlessly in hazard identification during the project execution on all construction activities and all over regions/climate areas. As a result, similar studies may be performed in several geographical locations (including several states in the United

States) to gather a broader sample of data and identify unique types of hazards. Second, only four of the most common and major construction activities were chosen for this study: roofing, concrete works, electrical, and mechanical work. Additional samples of construction industry practitioners are required to be recruited and surveyed to generalize future research findings to a larger audience (even worldwide). As a result, the findings of this study may not apply to other regions/countries.

On a different note, many other building practices necessitate extensive testing using various methods and techniques to recognize possible hazards fully. Another study can investigate the long-term visual and auditory effects of VR, (AR or MR) safety training platforms on humans to reduce potential hazards in construction activities. This study did play a unique role in the successful demonstration for BIM and VR usability in detection and mitigation of safety hazards, thus potentially creating a first step of very effective training procedures which could potentially lead to saving lives in this industry. The conclusions of this study can be further used to assist future research on enhancing construction operations' safety.

While conducting this research, there were several limitations. The data published by OSHA was used to analyze the procedure for delineating the four case studies of methodology. A set of 5,642 data points from the OSHA website on several states from 2015 to 2020 was downloaded. A general contractor supplied the company's data for the previous two months of work reflecting on behavior and environmental observations of their operations. In addition, another company (associated with a paper manufacturing plant construction) provided data sets that they had collected over one full year. The four case studies for this research were chosen based on the data analyzed from these construction-related organizations. The case studies conducted showed that these four major construction activities were the most vulnerable in Georgia's and its neighboring states. However, this information is insufficient to demonstrate the risks propagation in the industry's overall activities. The research can be conducted in many states to better comprehend the hazardous circumstances that may arise throughout the project implementation specifically to a different zone or a region. In addition, the number of case studies used in this study is relatively small. Lastly, there were not many survey responses received from the industry professionals during the Qualtrics survey deployment. Unfortunately, these limitations alone may be the subject for different results interpretations. For a better approach, case studies for well-known construction hazardous activities must be based on data collected intensively and over a longer period of time by several general contractors and subcontractors in the residential and/or commercial construction sectors throughout multiple US climate zones.

The case studies developed in this research were created and observed only by academic personnel. Testing the use of BIM inside VR HMD with construction professionals is needed for a better understanding of using this process of activity safety purposes and obtaining more accurate results. The observation of the models in the virtual environment to identify safety hazards may continue to be performed with industry participants on the actual job sites so that it becomes more feasible to understand and implement it in pre-construction and during construction phases. This process would also allow industry personnel to wander around into a virtual environment and to better understand future applied research. The data gathered from this real-world trial will aid researchers in determining whether deploying both BIM and VR devices is beneficial to safety (zero-injuries) and impact on human performance. So far, there are only a few construction businesses which have used 3D models in the virtual environment to identify potential hazards (in the SE-US region based on data investigated in this study). There may be many reasons behind this lack of adoption, including construction workers' lack of new technology knowledge, slow penetration in the market and less willingness to invest in advanced technologies due to being costly to deploy, and sometimes the fact that they are rarely required unless the clients on a large-scale project want them for evident benefit.

Further Recommendations

This study focused on the influence of using BIM and VR devices together on the detection and elimination of safety hazards during the pre-construction and/or execution of the project. It proposed the corroboration of BIM models and VR devices combined on their effect to the central issues causing hazardous situations in the construction process and the negative overall outcome it brings to the industry in case they go undetected. Further studies should focus on BIM and VR devices implementation on safety hazard identification on multiple (combined) construction activities and in different geographical locations. The sample size should be increased for future research to target the companies with BIM and VDC departments and eventually include experience from various associations like, the Associated General Contractors of America (AGC), Construction Management Association of America (CMAA), American Institute of Contractors (AIC), and other related organizations. The hazardous construction activities for this research were carefully selected only based on six different states of the Southeast United States regions. Therefore, further studies may be conducted with multiple construction activities thru other states (from other regions) to generalize the potentially meaningful results.

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APPENDIX A

SURVEY QUESTIONNAIRE

GEORGIA SOUTHERN UNIVERSITY

RESEARCH INTEGRITY

Institutional Review Board (IRB)
Veazey Hall 3000
PO Box 8005 • STATESBORO, GA 30460
Phone: 912-478-5465
Fax: 912-478-0719
IRB@GeorgiaSouthern.edu

To:	Maghiar, Marcel; Pangeni, Sudeep
From:	Eleanor Haynes, Director, Research Integrity
Approval Date:	4/28/2021
Subject:	Institutional Review Board Exemption Determination - Limited Review

Your proposed research project numbered **H21389,** and titled **"Safety hazards identification and minimalization using 3D NIM and the Virtual Reality through the case-studies.."** involves activities that do not require full approval by the Institutional Review Board (IRB) according to federal guidelines.

According to the Code of Federal Regulations Title 45 Part 46, your research protocol is determined to be exempt from full review under the following exemption category(s):

Exemption 2 Research involving only the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, if: Information obtained is recorded in such a manner that human participants cannot be identified, directly or through identifiers linked to them. Please visit our FAQ's for more information on anonymous survey platforms; Any disclosure of the human participant's responses outside the research could not reasonably place the participant at risk of criminal or civil liability or be damaging to the participant's financial standing, employ-ability or reputation; Survey or interview research does not involve children; The research project does not include any form of intervention.

Any alteration in the terms or conditions of your involvement may alter this approval. *Therefore, as authorized in the Federal Policy for the Protection of Human Subjects, I am pleased to notify you that your research, as submitted, is exempt from IRB Review. No further action or IRB oversight is required, as long as the project remains the same. If you alter the project, it is your responsibility to notify the IRB and acquire a new determination of exemption. Because this project was determined to be exempt from further IRB oversight, this project does not require an expiration date.*

Informed Consent
for
"Safety hazards identification and minimization using 3D BIM and the Virtual Reality through the case-studies."

1. Identify who you are, your relationship to Georgia Southern University, and why you are doing this research.
   My name is Dr. Marcel Maghiar, and I am an Associate Professor at Georgia Southern University in the Civil Engineering and Construction department. I am a principal investigator of this research and my graduate student Sudeep Pangeni from the same department is the co-investigator. This research is part of Sudeep's master thesis.

2. Purpose of the Study: This research aims to identify construction safety hazards on specific activities exposed to incidents with the integration of the 3D Building Information Modeling (BIM) and the Virtual Reality devices and how this training framework may help save lives or eliminate accidents/injuries in these construction activities.

3. Procedures to be followed: Participation in this research will include answers of 30 questions survey gathered through Georgia Southern Qualtrics.

4. Discomforts and Risks: We do not anticipate any risks from completing this study that will be greater than what you would encounter in day-to-day life. However, you may skip the questions that discomfort you or end the survey at any time without any kind of consequences.

5. Benefits:
   a. The benefits to you as a participant include understanding the nature of safety hazards before occurrence and finding ways to eliminate them from occurring. This research is also beneficial as an integral part of a master's thesis.
   b. The benefits to society include findings that may reduce hazards in the projected construction activities, which may lead to avoiding loss of life and other accidents.

6. Duration/Time required from the participant:
   The survey consists of 30 questions and should take about 20-25 minutes to complete.

7. Statement of Confidentiality
   Principal investigator Dr. Marcel Maghiar including a co-investigator, Sudeep Pangeni, will access this information using a shared drive. However, upon completion of this current research, the principal investigator may maintain it confidential for further research if needed.

8. Future use of data:

Collected data from this study will be placed in a secure location for study validation and further research. You will not be identified by name or other identifiers in the data set or any reports using information obtained from this study, and your confidentiality as a participant in this study will remain secure. Subsequent uses of records and data will be subject to standard data use policies that protect individuals and institutions' anonymity.

9. Compensation:
   This research survey will provide compensation in the form of an extra credit to only Georgia Southern students. The credit will be worth 3 points and applied to only one assignment with the lowest grade. The research survey will not provide any compensation to others outside of Georgia Southern University students.

10. Voluntary Participation: If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you do not want to answer and remain in the study until the survey ends. Georgia Southern civil engineering students will be receiving a 3 point of extra credit may also withdraw the survey at any time. They will still be eligible for an extra credit as soon as they start the survey even if they submit without all completion.

11. Penalty: There is no penalty for deciding not to participate in the study. You may choose at any time if you don't want to participate further and may withdraw without penalty or retribution.

12. Select based on what is most relevant to your study: You must be 18 years of age or older to consent to participate in this research study. As part of the study, you will be asked some of your demographic's detail, experience, and technology used for the proposed research. Your responses will be accumulated on the Georgia Southern Qualtrics platform.

You will be given a copy of this consent form to keep for your records. This project has been reviewed and approved by the GS Institutional Review Board under tracking number H21389.

Title of Project: "Safety hazards identification and minimization using 3D BIM and the Virtual Reality through the case-studies."
Principal Investigator: Dr. Marcel Maghiar, 912-478-5833, mmaghiar@georgiasouthern.edu
Other Investigator(s): Sudeep Pangeni, 984-244-3440, sp18103@georgiasouthern.edu
Research Advisor: Dr. Marcel Maghiar, 912-478-5833, mmaghiar@georgiasouthern.edu

For participants to indicate their agreement to take part in the research, select **one** of the options below based on what is most appropriate for your research methodology (e.g., in-person vs. online).

Option 1 (Online surveys):

Please select an option below to indicate whether or not you agree to participate in this research:

- Yes, I read the terms above and consent to participate in this research.
- No, I do not consent to participate in this research.

GEORGIA SOUTHERN UNIVERSITY
RESEARCH INTEGRITY

Institutional Review Board (IRB)
Application for Research Approval – Exemption 2, Limited Review

For Office Use Only: Protocol ID ______________

Please submit this protocol to IRB@georgiasouthern.edu in a single email; scanned signatures and official Adobe electronic signatures are accepted. Applications may also be submitted via mail to the Research Integrity Office, PO Box 8005.

Principal Investigator	
PI's Name: Dr. Marcel Maghiar	Phone: 912-478-8077
Email: mmaghiar@georgiasouthern.edu (Note: Georgia Southern email addresses will be used for all correspondence.)	Department: Civil Engineering and Construction College: CEC
Primary Campus: ☒ Statesboro Campus ☐ Armstrong Campus ☐ Liberty Campus	
☒ Faculty ☐ Doctoral ☐ Specialist ☐ Masters ☐ Undergraduate ☐ Other:	
Georgia Southern Co-Investigator(s)	
Co-I's Name(s): (M) Sudeep Pangeni (By each name indicate: F(Faculty), D(Doctoral), S(Specialist), M(Masters), U(Undergraduate), O(Other))	Email: sp18103@georgiasouthern.edu (Note: Georgia Southern email addresses will be used for all correspondence.)
Personnel and/or Institutions Outside of Georgia Southern University involved in this research:	
	☐ IRB Approval Attached *(Reliance agreements not available on exempt protcols.)*
	☐ IRB Approval Attached *(Reliance agreements not available on exempt protcols.)*

Project Information	
Title: **"Safety hazards identification and minimization using 3D BIM and the Virtual Reality through the case-studies."**	
Number of Subjects (Maximum) 700	
Will you be using monetary incentives (cash and/or gift cards)? ☐ Yes ☒ No	
☒ Self-funded/non-funded ☐ Internal Georgia Southern Internal Source:	☐ External Funding (*You are responsible for duplicate or additional approval submissions required by funders.)* Funding Source: ☐ Federal ☐ State ☐ Private ☐ Contract Funding Agency: Grant Number: 39G

	Grant Title: ☐ Same as above Enter here: ☐ Funding application scope of work attached

Compliance Information
Do you or any investigator on this project have a financial interest in the subjects, study outcome, or project sponsor? (A disclosed conflict of interest will not preclude approval. An undisclosed conflict of interest will result in disciplinary action.). ☐ Yes ☒ No (If yes attach disclosure form)

Certifications

I certify that the statements made in this request are accurate and complete, and if I receive IRB approval for this project, I agree to inform the IRB in writing of any emergent problems or proposed procedural changes. I agree not to proceed with the project until the problems have been resolved or the IRB has reviewed and approved the changes. It is the explicit responsibility of the researchers and supervising faculty/staff to ensure the well-being of human participants.

Signature of Primary Investigator
Date 03/24/2021

Signature of Co-Investigator(s):
Date 03/24/2021

By signing this cover page I acknowledge that I have reviewed and approved this protocol for scientific merit, rational and significance. I further acknowledge that I approve the ethical basis for the study.

If faculty project, please have department chair sign; if student project, please have research advisor sign:

David W. Scott Typed/Printed Name	Signature	04/26/2021 Date

Instructions: Please respond to the following as clearly as possible. The application should include a step by step plan of how you will obtain your subjects, conduct the research, and analyze the data. Make sure the application clearly explains aspects of the methodology that provide protections for your human subjects. Your application should be written to be read and understood by a general audience who does not have prior knowledge of your research and by committee members who may not be an expert in your specific field of research. Your reviewers will only have the information you provide in your application. Explain any technical terms, jargon or acronyms. Read the entire form before beginning to limit repetition in responses.

Exemption 2: Research that includes interactions involving educational tests (cognitive, diagnostic, aptitude, achievement), Survey procedures, interview procedures, or observation of public behavior (including visual or auditory recording) without additional intervention if at least one of the following criteria are met:

1. *The information obtained is recorded by the investigator in such a manner that the identity of the human subjects cannot readily be ascertained, directly or through identifiers linked to the subjects.*
2. *Any disclosure of the human subjects responses outside of the research would not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects financial standing, employability, educational advancement or reputation:* ***or***
3. *The information obtained is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects, and an IRB conducts a limited review to make the determination required by 45 CFR.111 (a) (7)*

DO NOT REMOVE THE QUESTIONS/PROMPTS.

1. Personnel
Please list any individuals who will be conducting research on this study. This includes the principal investigator, co-investigators, and any additional personnel. Also, please detail the experience, level of involvement in the process, and the access to information that each may have.
Associate Professor Dr. Marcel Maghiar will be involved as a PI and a Graduate student, Sudeep Pangeni, as a Co-investigator for this research. Co-investigator is knowledgeable and has experience related to construction technologies such as 3D modeling software, Virtual Reality devices relevant to this research. The collected information will be accessed confidentially between the principal investigator and co-investigator in the shared drive.

2. Project Description
Briefly describe in one or two sentences the purpose of your research.
This research aims to perform a survey, both quantitative and qualitative using questions related to the construction activities collected through the case studies. The gathered data will be analyzed to identify and potentially minimize hazards pertaining to these activities.

3. Describe Your Subjects
A. *Briefly describe the study population.*
A group of Civil engineering and construction management students, safety managers, project managers, assistant project managers, and superintendent will be included in the survey population.
B. *Applicable inclusion or exclusion requirements (ages, gender requirements, allergies, etc.)*
There is not any inclusion of ages, gender requirements, allergies for this survey.
C. *How long will each subject be involved in the project? (Number of occasions and duration)*
<u>The survey consists of 30 questions, and it should take about 20-25 min to complete</u>. The survey is taken only once by everyone. The survey may be deployed several times over a week.

4. Recruitment and Incentives
A. *Recruitment: Describe how subjects will be recruited. (Attach a copy of recruitment emails, flyers, social media posts, etc.) DO NOT state that participants will not be recruited.*
<u>The subjects will be recruited through the Georgia Southern Qualtrics. Questionnaire will be recruited to the safety professionals within the U.S. using the Georgia Southern email.</u>
B. *Are you compensating your subjects with money, course credit, extra credit, or other incentives?* ☒ **Yes** ☐ **No**
C. *If yes, indicate how much, how they will be distributed, and describe how you will compensate subjects who withdraw from the project before it ends.*
<u>*Students will be recruited via an advertised announcement that will be published in the class Folio, and this announcement will provide a link to the Qualtrics survey. Extra credit will be provided to Civil Engineering and Construction Management students on the Georgia Southern campuses who actively engage in the survey. The extra credit is worth three points and will be applied to the assignment with the lowest score. Even if they do not finish the survey or miss any questions, they will receive extra credit. The professor will offer extra credit to students who upload a screenshot of the completed survey (thank you note) to the dropbox.*</u>

5. Describe Your Procedures
A. *Which statement best describes the procedures in this protocol (including recruitment, consent, interventions, etc,)?* ☒ This data is being collected without ANY in person interactions with participants (ie. online surveys, virtual interviews, etc.)

☐ This data is being collected in person with participants but without any direct physical contact (ie. in person interviews, in person focus groups, etc.). **Safety Plan REQUIRED** ☐ This data requires direct physical contact with participants (ie. placing sensors on a participant, etc.) **Safety Plan REQUIRED**
B. *Describe the research project elements in sufficient detail to allow reviewers to understand your project. Clearly and briefly describe the methods you will use in terms of what participants will be asked to do and how the data will be handled.*
This survey asks about your experience working with 3D Building Information Modeling (BIM), Virtual Reality devices, and safety training to tackle construction-related hazards. A set of 30 questions related to construction safety, Building Information Modeling, Virtual, Augmented, and Mixed Reality will be released through Qualtrics. The data will be downloaded in the form of an excel sheet or pdf through the Qualtrics. In addition, the gathered data from the Qualtrics will be handled using a shared drive among the PI and co-PI.
C. *Describe how legally effective informed consent will be obtained. (Also, attach a copy of the consent form(s).)* ☒ For surveys: The consent will be included as the first question in the survey. The consent will include a statement that certifies that by proceeding with the survey, participants acknowledge agreement to the consent. ☐ For interviews: The consent will be provided to participants prior to the interview. Participants will be asked to verbally consent before the interview can proceed. ☐ Other Method:
D. This exemption will not apply if any of the following are Yes. ☐ Yes ☒ No Is the probability or magnitude of the harm, harassment or discomfort anticipated in the proposed research greater than that encountered ordinarily in daily life or during the performance of routine physical or psychological examinations or tests? ☐ Yes ☒ No Does the project involve school children in any process other than observation of public behavior? ☐ Yes ☒ No Are you a participant in classroom behavior being observed (including as classroom moderator)? ☐ Yes ☒ No Are any of the potential participants prisoners or clients of the adult or juvenile justice system? ☐ Yes ☒ No Does the project involve active or passive deception? ☐ Yes ☒ No Could the subject matter be considered beyond local social, ethical or cultural bounds? ☐ Yes ☒ No Is there an intervention included in the elements of this project (If yes, apply using exemption 3)?
E. You project will include (Check all that apply): ☒ Survey ☐ Interview ☐ Observation of public behavior ☐ Use of educational tests (received by researcher without identifiers or with

	FERPA clearance in letter of cooperation from school.)
F. Will any *information be obtained that is recorded by the investigator in such a manner that the identity of the human subjects can readily be ascertained, directly or through identifiers linked to the subjects including extensive demographics*? ☐ **Yes** ☒ **No** ☐ **N/A**	
G. *If yes, describe how you will protect participant privacy and confidentiality (E.g., secured storage location, removal of identifiers following transcription or matching of data, private room for focus group).*	
H. How will interviews be conducted? ☐ In Person ☐ Virtually using the following platform: ☐ Zoom ☐ Google Meet ☐ via Telephone ☐ Other: ☒ **Not conducting interviews**	Will interviews be recorded? ☐ Audio Recording ☐ Video Recording ☐ N/A How will recordings be maintained? ☐ Destroyed after transcription or analysis. ☐ Identifiable and maintained per consent. ☐ De-identified and maintained per consent.
I. How will online surveys be gathered? ☒ Anonymous ☐ Confidential (For more than minimal risk, exempt 2 does not apply) Identify the online survey platform AND security setting to be used: **Survey Platform**: ☒ Qualtrics ☐ SurveyMonkey ☐ Other: **Security Setting**: ☒ Manually disable tracking of IP addresses and identifiable information ☐ Other: ☐ **Not collecting survey data online**	
J. Will recruitment be distributed to @georgiasouthern.edu email address (es) (this includes email lists you already have access to and Georgia Southern listservs)? ☒ **Yes** ☐ **No** ☐ **N/A** (If yes, see the GS survey distribution policy)	

K.	If collecting a live (classroom) or public area survey, will the surveys be collected utilizing a drop box or other blind method to allow participants to choose not to participate without alerting the researcher/moderator? ☐ **Yes. Describe the process:** ☐ **No. Describe methods to protect participants**. ☒ **Not collecting live surveys**
L.	Will any data be collected that could, if disclosed, reasonably place participants at risk of criminal or civil liability, or be damaging to the participants financial standing, employability or reputation? ☐ **Yes. Please describe:** ☒ **No**
M.	Will any individually identifiable data be collected? ☐ **Yes. Please describe:** ☒ **No**
N.	Are participants: ☒ **Over 18** ☐ **Under 18.** If under 18, how will you obtain parental permission for this study?

6. Data Analysis	
A.	*Briefly describe how you will analyze and report the collected data.*
	The received data will be statistically tested using R software. Hypothesis will be created and later validate the collected data using linear regression analysis and the p-test. Linear regression is used to describe a relationship between two different variables. Also, the correlation and directionality of the data can be analyzed and evaluate the validity and the usefulness of the model. Lastly, p-value obtained from the sample of data will be used to calculate the significance of the hypothesis and conclude whether the result rejects the null hypothesis or fails to reject the null hypothesis.
B.	*Include an explanation of how will the data be maintained after the study is complete. Specify where and how it will be stored (room number, password protected file, etc.)*
	All data received will be kept confidential in a shared drive by the principal investigator and co-investigator. We do not further seek to share data at this point with external parties.
C.	*If this research is externally funded (funded by non-Georgia Southern funds), student researchers must specify which faculty or staff member will be responsible for records after you have left the university. The person listed below must be included in the personnel section of this application.*
	Responsible Party: Dr. Marcel Maghiar (Internal funds were only obtained) ☐ **N/A**

D. Anticipated destruction date or method used to render data anonymous for future use. Please make sure this in consistent with your informed consent. ☐ Destroyed 3 Years after conclusion of research (minimum required for all PIs) ☐ Other timeframe: ☒ Maintained for future use in a de-identified fashion. Method used to render it anonymous for future use: Shared via Google Drive only between PI and co-PI *Note: Your data may be subject to other retention regulations (i.e. American Psychology Association, etc.)*

Attachments
☒ **Informed Consent attached. (See Informed Consent checklist for criteria)** ☐ **Informed consent or element of consent waiver requested** **Attach the Waiver Request form (Complete Table 1 for complete waiver** (e.g., a study that will only use classroom data from assignments that students will complete regardless of the research and data for this study will be recorded for study analysis and reported without individual identifiers and written FERPA statement is attached (This should be described in your application.) **and table 2 for alteration of one or more elements. (**e.g., waiver of signature on consent form where data is anonymous**)**
☐ **Letter of Cooperation (LOC)/site authorization attached –** ☐ **No data will be gathered from sources outside of my department or will be gathered without use of another sites resources (e.g., participant access or business time, student/school access)** ☐ **This research is done upon the request of the performance site.** ☐ **Site authorization will be requested upon IRB approval. I understand that the LOC will be required as a condition of approval/determination.** **LOC Notes**: (If education data is requested, the permission must include a statement indicating if the data can be accessed for research purposes and if parental permission is required under the entities FERPA policy.) <u>Access to student data for teaching purposes does not provide access for research use</u>. See letter of cooperation sample on the GS IRB forms website. Sample format is not required.
☒ **Survey, interview questions, focus group plan or other handouts that may assist to illustrate your project attached.**

Demographics Questions:

1. What type of construction company are you working with?

General contractor | Sub-contractor _____________(what trade?)

Small renovation contractor | Owner-Builder

Real estate developer | Design-Built Contractor

Anything else ______________(please be specific)

2. What kind of construction projects are mainly carried out by your company?

Residential building construction | Commercial building construction

Industrial construction | Bridge construction

Highway construction | Anything else______________

3. What is your role in your workplace?

Project Management | Assistant Project Manager

Safety Management | Superintendent

Civil/Construction Engineering Student | Others (please specify) ______________

Activity Questions:

4. Type of construction activities most performed by your company (select all, if applicable)

Concrete work (residential / commercial) | Electrical work

Mechanical work (construction related) | Roofing activities

Framing (Interior and Exterior) | Others (please specify) ___________

5. During what construction activities (areas) do you find that hazards are mostly recognized?

Roofing activities | Concrete works

Electrical works | Mechanical works

Framing works

Steel erection

Others (please specify) ___________

Masonry works

Safety Professionals and Activity Hazards

6. Does your company have a safety engineer/manager on site?

Yes   External 3rd party   In-Progress hire   Maybe soon   Not planned yet

7. How do you approach safety if any hazards occur during the actual construction?

Call Superintend to the site

Call Safety Manager to the site

Call Project Engineer to the site

Call Project Manager to the site

Request an office meeting with all involved

Other (please specify)_______________

8. Are safety hazards tracked using construction technology applications to potentially eliminate them from reoccurring? (Choices of devices/forms used)

Mobile phone

iPad / Tablet PC

Web Portal

Excel Sheet or other tabular forms

Other technology means (please specify app or technology) __________________

9. Are there any repetitive hazards identified by your company? If any, please describe (open-ended question, max. 150 words)

(____)

10. Are there any potential hazards occurring during concrete activities in your company?

Concrete forming & pouring

Concrete cutting

Concrete mixing truck

Concrete leveling mechanical devices

Rebar cutting/sizing

Tower cranes (lifting concrete to multiple floors)

Concrete work inspection

Others (please specify)_________________________

11. Are there any potential hazards occurring during the use of electrical equipment in your company?

Moving or placing electrical poles   Installing electrical cords/ducts, switches, etc.

Laying open electrical wires   Replacing light fixtures

Inspecting on-site electrical works   Others (please specify)_______________________

12. Are there any potential hazards occurring during the operation of mechanical equipment in your company?

Aerial and scissor lift operations   Tower cranes (Lifting materials)

Running heavy vehicles (loading and unloading)   Operating forklifts

Dozer/Excavator work   Others (please specify)____________

13. Are there any potential hazards occurring during the roofing activities in your company?

Installing trusses   Placing ceilings

Working anchors from the roof edge   Inspecting roof leaking/roof cleaning

Pacing or removing shingles   Others (please specify) ____________

14. What are the sources of hazards occurring in your construction activities? (select all that apply)

Ladders   Scaffoldings   Oil/chemical spills

Open slabs   Aerial and scissor lifts

Weather conditions   Mechanical/Electrical equipment (including power tools)

Others (please be specific)____

15. Does the company have plans for specific improvements to promote and to minimize these safety hazards?

Use more safety-related technologies (_____)   Hire more safety professionals

Provide safety training more often   Perform more safety awareness programs

Provide incentives for specific safety goals   Others (please specify)__________________

Safety Training

16. Safety training frequency of construction professionals/trade workers in your company is:

Twice a week Every week Every Month Quarterly Biannually
Others (please specify)______________________

17. What level of training, qualifications or experiences are required to guide your company's safety approach?

Very high (10 yrs.) High (5+) Neutral (3-5 yrs.) Low (1-2) Minimum(< 1 yr.)

18. Safety and Personal Protective Equipment is tested and verified before every use in the field

Always Frequently Depends (condition of PPE) Infrequently Only when needed

19. Frequency of Safety Inspections in your company is occurring

Twice a week Every week Monthly Quarterly Twice a year
Other frequency (please specify) _______________________

Mitigation of Hazards / Dangers

20. How does your company mitigate behaviors (environmental or human) for hazardous activities performed on-site? (open-ended question, max. 150 words)

(____)

Technology Usage and Advance Devices Training (YES/NO; Go - No Go)

21. Does your company involve a BIM person within the VDC Department for safety-related matters?

Yes External 3rd party Hiring (In-Process) Planning soon Not planned yet

22. In your opinion, what is the probability of identifying hazards during your projects' design phase?

0-20%(very low) 20-40%(low) 40-60% (average) 60-80% (high) 80-100% (very high)

23. How are hazards considered and eliminated from the design phase? Do you believe using BIM in this process played a significant role in hazard identification/minimization in your company? (open-ended question, max. 150 words)

(____)

24. Does your company use virtual/augmented reality devices for employee safety training in the virtual environment?

Never Rarely Sometimes Often Always

Device/Software_

25. Does your company implement Virtual, Augmented, or Mixed Reality (VR/AR/MR) to identify possible design errors and a better approach to safety hazards?

Never Rarely Sometimes Often Always

26. Were the Virtual Reality tools (if used) helpful for identifying, minimizing, and sometimes eliminating hazards in your company?

Strongly Agree Agree Neutral Disagree Strongly Disagree

27. Has your company integrated 3D BIM models in conjunction with VR/AR/MR devices for design and construction safety purposes?

Not at all Rarely Sometimes Often Almost always

28. Does your company integrate 3D BIM models and VR/AR/MR devices to approach safety hazards in virtual laboratory/site?

Not at all Rarely Sometimes Often Almost always

29. Please identify an approximate average percentage of the real hazards present per project in your company after integrating 3D BIM models with VR/AR devices:

0-20% (very low) 20-40%(low) 40-60% (average) 60-80% (high) 80-100% (very high)

Overall Perceived Performance

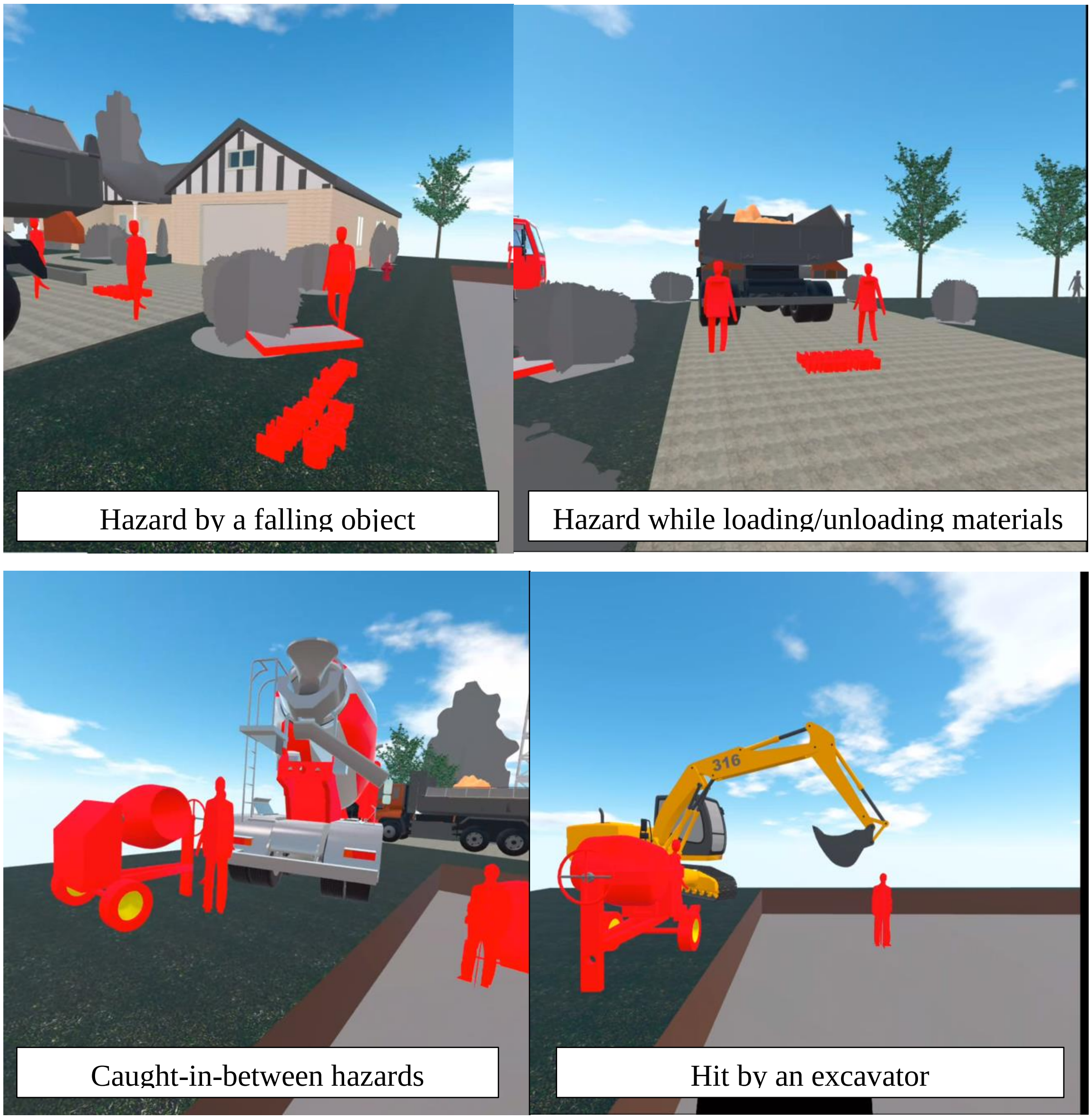
30. In your opinion, what is the overall perceived safety performance at your company for construction professionals?

Poor/Minimal Satisfactory Average Good Excellent

APPENDIX B

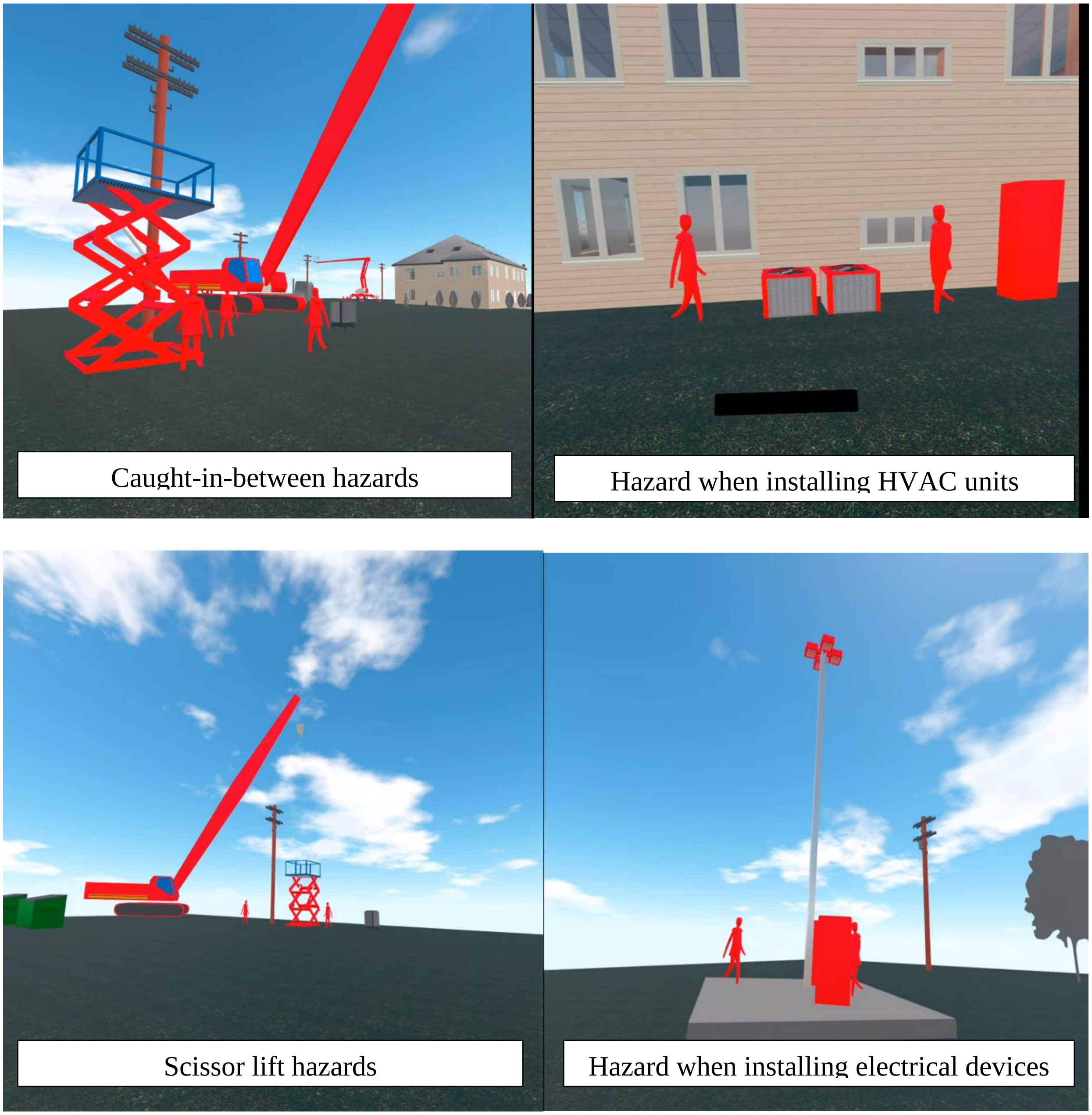
SAFETY HAZARDOUS SCENARIOS TESTING ON THE 3D MODEL

Concrete works



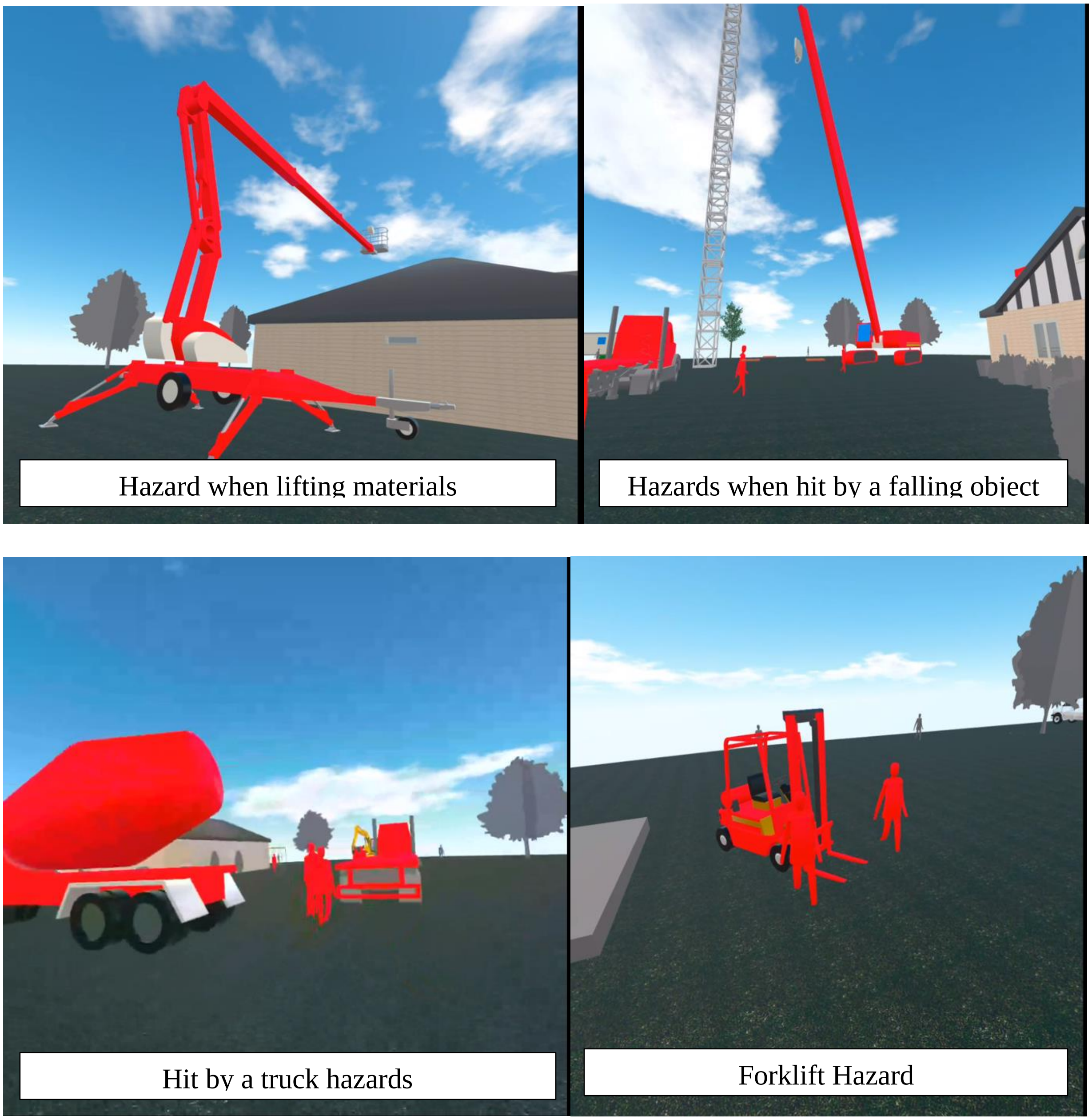
(Shared GDrive folder for Concrete Work)

Electrical Equipment works



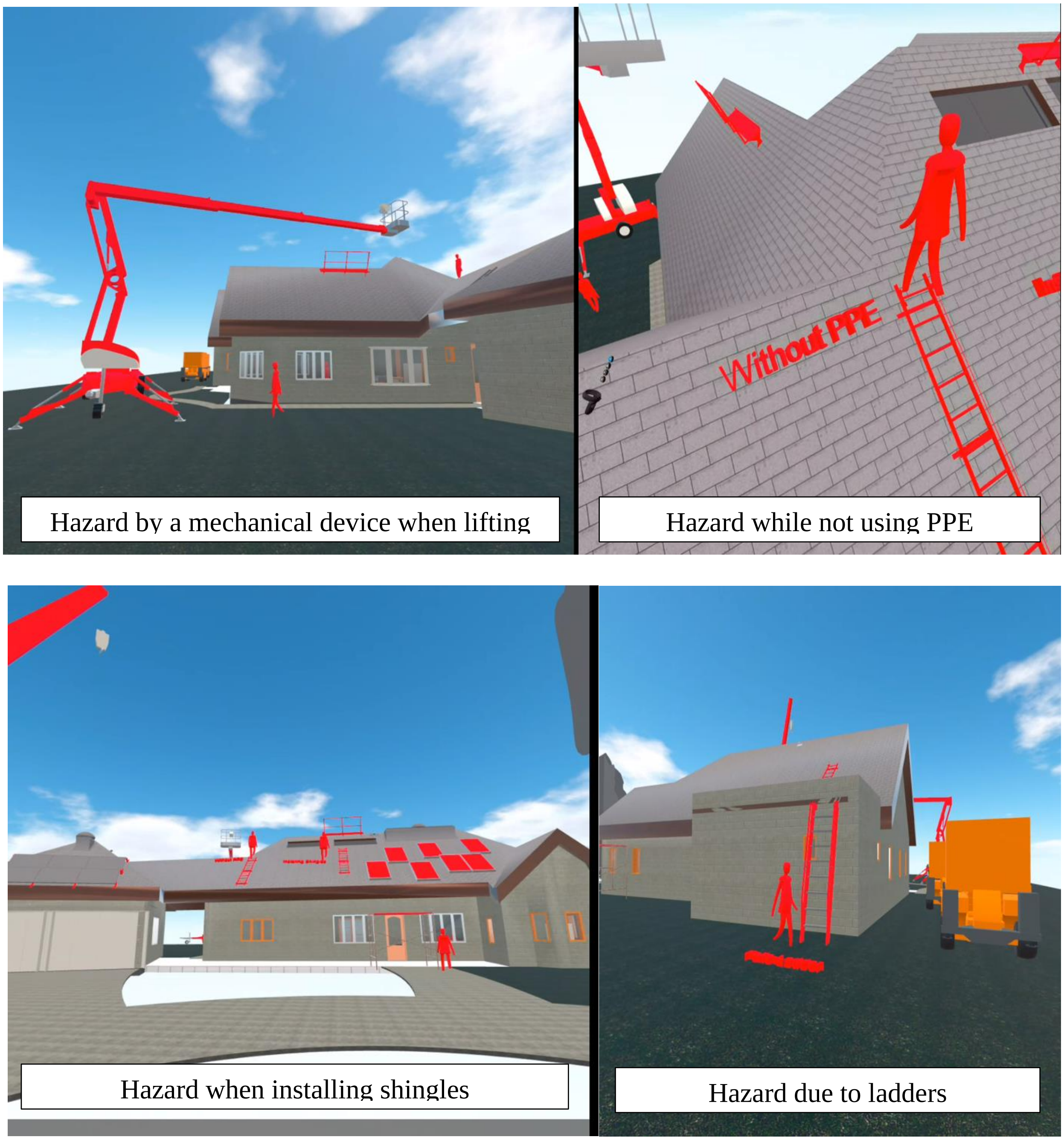
(Shared GDrive folder for Electrical Equipment Work)

Mechanical Equipment Works



(Shared GDrive folder for Mechanical Equipment Work)

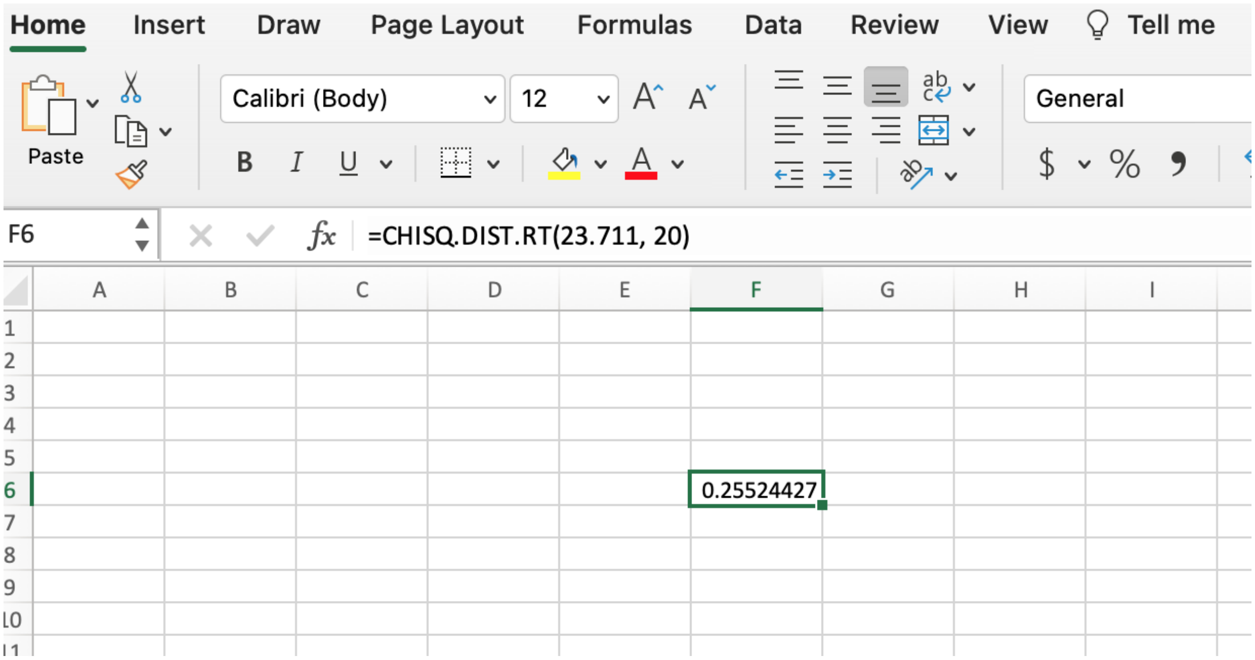
Roofing Works



(Shared GDrive folder for Roofing Works)

APPENDIX C

CALCULATION OF P-VALUE INTO MS EXCEL ENVIRONMENT



The one-tailed probability of the chi-squared distribution is calculated using the parameters provided in the value at which you want to evaluate the distribution and the degrees of freedom. The right-tailed probability of the chi-square distribution will be calculated using the Excel statistical function CHISQ.DIST.RT. This function is used to compare the observed and expected values and get the p-value. The value of chi-square (χ^2) is 23.711, degree of freedom (df) is 20, and the p-value (p) to be 0.255 ($\chi^2(20)$ =23.711). The p-value is calculated by using the formula in Excel sheet (=CHISQ.DIST. RT (23.711, 20)) which is equal to .255.