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Increasing workers' safety by using Virtual Reality (VR) in the project design and production planning

Master's thesis in the master's Program Design and Construction Project Management

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Abstract

Construction sites pose inherently hazardous work environments due to the nature of the work involved. As such, the industry is known for its high rate of accidents and injuries compared to other industries which makes improving the safety of construction workers of paramount importance. This study examines the use of cutting-edge virtual reality (VR) technology to enhance the safety planning of construction projects in the design and planning phase. The study is built on a qualitative approach based on a literature review and an empirical study. The empirical study includes a workshop with two design engineers, a health and safety engineer, a VDC Developer and several researchers as participants. The findings from this study indicate that VR offers significant advantages over traditional 2D drawings in terms of safety planning. Immersive VR walkthrough can provide a more comprehensive representation of the project, aiding in the planning and implementation of effective safety measures. Moreover, the findings highlight that collaborative VR walkthroughs have the potential to enhance safety planning by improving communication and coordination among project stakeholders and the use of VR can increase safety awareness among design engineers, equipping them with the knowledge and mindset necessary to proactively address potential hazards. The study recommends the combination of VR with touchscreen boards for effective site planning and collaboration, acknowledging that VR technology is an immature technology which requires further research and advancement. Additionally, the study identifies some areas where future research should focus on.

Keywords: collaboration, construction, design engineer, hazards, safety, virtual reality, 2D drawing.

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Abbreviations

VR- Virtual Reality

VDC- Virtual Design and Construction

2D- Two Dimension

3D- Three Dimension

AEC- Architecture, Engineering, and Construction

BIM- Building Information Modelling

RQ- Research question

SDG- Sustainable Development Goals

H&S- Health and Safety

PC- Personal Computer

HMD- Head-Mounted Display

CAVE- Computer-Aided Virtual Environment

SID- Spatially Immersive Display

JHA- Job Hazard Area

DFSP- Design for Safety Process

TV- Telecommunication Medium

MUVR- Multi-User Virtual Reality

SUVR- Single User Virtual Reality

CoVR- Collaborative Virtual Reality

VoIP- Voice over Internet Protocol

OSHA- Occupational Safety & Health Administration

PtD- Prevention through Design

CII- Construction Industry Institute

NIOSH- National Institute of Occupational Safety and Health

HBR- Houston Business Roundtable

HVAC- Heating, Ventilation, and Air Conditioning

PVC- Polyvinyl Chloride

DfS- Design for Safety

US- United States

CDM- Construction Design and Management

BREEAM- Building Research Establishment Environmental Assessment Method

BENQ- Bringing Enjoyment N Quality

MEP- Mechanical, Electrical, and Plumbing

R&D- Research and Development

IFC- Issue for Construction

AI- Artificial Intelligence

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1. INTRODUCTION

This chapter of the study briefly introduces the background and context of the study on ‘increasing workers’ safety by using Virtual Reality (VR) in the project design and production planning’. Furthermore, it describes the problem statement and research questions that were investigated. This chapter also includes the delimitation of the study and the description of the structure of the report. In addition, some sustainability and ethical considerations regarding the study are presented in the chapter.

1.1 Background

Due to the frequent mobility of the work and the temporary nature of the workplaces, construction is one of the industries with the highest rate of serious work-related accidents (Swedish Work Environment Authority, 2022). Depending on the unique project conditions there are always new situations, new risks, hazards, and dangers. Guo et al. (2017) mentioned as per global statistical data, in the construction industry, fatal accidents is three times higher, and injury is twice as high as other industries, and the accident rate continues to be higher. Again, the rate of non-fatal injuries in the construction industry was 71% higher than in all industries (Zeng & Li, 2022). Since the construction industry is notorious for accidents and health hazards, there is significant potential for improvement when it comes to enhancing the safety of construction site personnel. Moreover, construction industry frequently suffers from lack of space and equipment, machines, material storage areas resulting in lower available space on site that increases safety issues and potentially hazardous areas. As each construction project is unique in nature, identifying all potential hazards and risks becomes challenging which is why workplace safety is a critical issue in the construction industry (Azhar, 2017). Therefore, proper planning for safety is vital for preventing hazards and creating a safe work environment.

Several research studies demonstrated that undertaking preventative measures into building design, planning and construction phase decrease site accidents and improve productivity (Getuli et al., 2018). However, in case of traditional construction safety planning, safety managers and workers have to imagine construction site scenarios according to the project drawings and documents that hinder proper planning process (Guo et al., 2017). The application of state-of-the-art technology such as VR can digitally simulate the construction site context in which project teams could identify and learn about safety hazards without physically exposing them to the actual hazards (Sacks et al., 2015). Although BIM based VR has various applications in the AEC industry such as design reviews, production planning, and construction safety training (Johansson & Roupé, 2022), there exists a gap in knowledge and limited research on utilizing VR for construction safety planning in the design and planning phase. Through analyzing the construction practitioners’ view, this study would, thus, propose how VR can be used in better planning for safety in the project development and production planning phase so that risks and accidents during the construction phase can be avoided and a safer construction site can be ensured. Therefore, the purpose of this study is to investigate the potential of VR in producing safer planning and design solutions for construction site personnel.

Furthermore, communication and information sharing are crucial for construction projects as poor communication could result in misunderstandings, affecting the project performance in terms of quality, time, cost as well as safety (Du et al., 2018). Johansson & Roupé (2022) investigated the

benefits of multi-user VR in a construction-oriented context and suggested that multi-user VR can improve communication and planning and can significantly enhance collaboration between design and production team. Thus, this study would further explore, if VR can facilitate collaboration between design and collaboration team and help bringing construction knowledge into the planning phase in order to improve safety planning and raise design engineers' awareness regarding safety issues. Raising design engineers' awareness regarding safety issues is essential because design engineers have a significant influence on construction project outcomes, including the safety of workers. Neglecting safety considerations during the design phase can lead to hazards and risks that could have been prevented or minimized. Increasing design engineers' awareness of safety issues can enable them to proactively identify and address potential risks, leading to better safety outcomes in the construction industry (Gambatese & Hinze, 1999).

1.2 Problem statement and research questions

Construction sites are known as one of the most stressful and physically demanding workplaces among various industries. As such, the rate of accidents is among the highest in the construction industry compared to all other industries (Azhar, 2017). Thus, it is crucial to implement improved accident prevention strategies and strengthen safety management. In traditional safety management, potential safety hazards are identified through safety managers' or project managers' experiences and prevented through safety training and onsite safety monitoring (Guo et al., 2017). Therefore, potential hazards remain unidentified and are only exposed during the actual construction process. Since VR could closely represent the actual job site conditions, it is more likely to identify hazards than 2D static drawings (Azhar, 2017). VR can be used to simulate construction processes in a virtual environment that can be used in repetition and the scenario can be easily perceived by the participants (Yan et al., 2022). Despite the benefits from studies that have been proven, the industry is currently not exploring the benefits of VR for safety planning and collaboration. Thus, by utilizing VR, this study aims to improve safety planning by identifying and addressing safety issues in the design and production planning phase in order to improve safety performance. Furthermore, since the construction industry is fragmented, one of the major challenges faced by the industry is facilitating collaboration and mutual sharing of information among various stakeholders (Getuli et al., 2020). Communication systems in a construction project are not efficient which hinders proper collaboration. Thus, this study will further investigate if multi-user VR as a collaborative tool facilitates safety planning process and contribute to increasing design engineers' knowledge regarding construction site and safety issues.

Research questions: To achieve the goal of the study, the following research questions will be investigated:

- RQ1. Can VR improve project safety planning in comparison to 2D drawings?
- RQ2. Can VR as a collaborative tool help and facilitate better safety planning?
- RQ3. Can VR aid in increasing the awareness of the design engineers regarding safety?

1.3 Delimitation

The study focused on implementation of VR only in the planning phase. Again, although the study involves investigating use of VR in terms of increasing design engineer's awareness regarding safety, during the research only the structural engineers were included as design engineers. Other design engineers such as MEP engineers and architects were not included in the study, therefore, their influences in improving safety could not be analyzed. Because of time limitations, the scope of the research was limited to conducting one workshop for data collection. Further limitations can be the literature review involved in this research are studies from different countries' backgrounds, on the other hand, the empirical study involved examining only one case project from Swedish context. Thus, the results of the study cannot be generalized. Moreover, except for three studies (1992, 1997 and 1999), the literature used in this study was published between 2011 and 2022, and only English literature were used.

1.4 Description of the report's structure

The first chapter gives a brief introduction to the subject of the study and describes the background of the study. After that, this chapter presents the research questions that were investigated and acknowledges some limitations of the study. This chapter also includes the description of sustainability and ethical considerations that were undertaken during the research. The second chapter introduces the research methodology of the study. Following that, the third chapter provides the results of brief literature review from the existing body of research. The fourth chapter includes description of chosen project and case, explanation of the processes for preparing different simulated scenarios for VR walkthrough and brief introduction of VR features. This chapter further describes sequentially the various activities that were carried out during the workshop for the empirical study. Thereafter, the fifth chapter presents the results and findings of the workshop activities. The following chapter includes the discussions addressing the stated research questions and outlining the key findings of the study. The final chapter presents the conclusion, limitations of the study and some suggestions for future areas of research.

1.5 Sustainability and Ethical Considerations

Sustainability concerns

This study makes several contributions to sustainability concerns. This study looks into how to identify risks and hazards so that accidents can be prevented or reduced. Therefore, by reducing risks and accidents, it contributes to economic sustainability, and by aiding in the improvement of health and safety of the workers, it promotes social sustainability. As a result, this study significantly contributes to SDG3, which strives to guarantee healthy lives and promote well-being for all people, regardless of age. Goal 3 further advocates for greater investment in health financing and health risk reduction and management, and research and development. The findings of this study are also in support of education and training. Through this, it promotes SDG4, which stands for quality education. Additionally, by ensuring a safe construction process, this study supports SDG9-Building sustainable industry and infrastructure, SDG11-Building sustainable cities and communities, and SDG12-Ensuring sustainable consumption and production.

Ethical considerations

There are two main ethical considerations that were taken into account when conducting this master thesis research, which includes confidentiality and results communication. The information gathered throughout the study was kept confidential. To ensure the privacy of the case company and its personnel, any identifying information was removed from the data before its use in the research. Only the researchers and supervisors, who were knowledgeable about Chalmers' data confidentiality procedures, had access to this information. Another ethical consideration in this thesis is the proper communication of research results, which includes avoiding plagiarism and research misconduct. All sources of information used in the research are properly cited and not plagiarized. The study clearly outlines the research approach and data collection techniques. The research was conducted in a thorough manner, with an appropriate methodology, analysis, and interpretation of results. It includes appropriate research questions, and the results presented are supported by the data collected. The thesis was conducted with academic integrity and ethical standards, with no indication of making up or falsifying data, and misrepresenting results in research reports. The systematic literature study and empirical study develop a general overview of the topic.

Again, utilizing a workshop as a tool for data collection enhances ethical consideration of the research by fostering a sense of community and trust among participants, leading to more reliable and trustworthy data collection and interpretation. By encouraging open and honest responses and ensuring equitable involvement, workshops contribute to the overall trustworthiness of the gathered data in research studies (Ahmed & Asraf, 2018). During the workshop, both video and audio recordings were made, which were done with permission from all participants.

2. METHODOLOGY

This study had a qualitative method with inductive strategy and was carried out through conducting a systematic literature review and an empirical study. To develop a general overview of the topic, several scientific articles and reports were collected and assessed with the help of search engines like Chalmers Library, Google Scholar, Science Direct, and Research Gate. Combinations of search words were used such as ‘workers’ safety’, ‘safety practice in construction industry’, ‘safety management’, ‘hazard identification’, ‘work environment in construction’, ‘virtual reality’, ‘multi-user VR’, etc. After a deeper understanding of the current research of the concept, a literature gap was identified and accordingly research questions were formulated.

For the empirical study, a 3-hour workshop was conducted with various construction professionals and academicians. Because the research has specialized topics, workshops offer valuable opportunities for researchers to explore specialized subjects by engaging with a small group of participants, resulting in detailed and unique data that surveys or interviews may not capture (Ahmed & Asraf, 2018). Furthermore, workshops facilitate a collaborative environment where participants can exchange their experiences and insights, which was one of the main purposes of the study.

The workshop included multi-user VR walk through within a virtual site scenario resembling construction process for hazard identification and discussion of hazard preventive safety measures. To develop scenarios for the walk through via VR, a BIM model of the project Kineum, managed by the company NCC, was used. It should be noted that this study is conducted in collaboration with the company NCC. NCC is a leading construction company in the Nordics and Kineum is one of their latest completed commercial property development projects.

To develop a proper workshop agenda and formulate questions for the participants, several meetings and discussions were conducted with structural design engineers, a safety engineer, a lead VDC developer and researchers. Furthermore, relevant information and data was collected from NCC’s safety documents and H&S database. and. To simulate the VR scenarios, the BIM model of the Kineum building and relevant BIM components were imported to the software BIMXplorer V1.7.5 (BIMXplorer, n.d.). Utilizing the interface of a touchscreen board, the BIM components were set up in the BIM model and various site scenarios were simulated as required.

The workshop was divided into five parts of activities – a 2D exercise, a VR exercise, a site layout plan discussion, a presentation of a safe scenario through VR and answering reflection questions. In the 2D exercise, the participants were provided with 2D plans of the 6th floor of Kineum project where they were asked to identify hazards and discuss safety measures. For the VR exercises, two VR headsets were set up at the two opposite sides of the room. One of the headsets was connected to a laptop screen and the other one was connected to a projector screen. Through the laptop screen and projector screen other participants could observe the activities of the person using the VR headset. In addition, a touchscreen board was set up in the middle of the room where the BIM model can be seen, and the avatars of the VR headset users were visible. During the VR exercise, the participants were asked to identify hazards in a simulated unsafe construction scenario through multiuser VR walk-through. In this case, an unsafe site scenario refers to a lack of appropriate safety equipment and a high risk of accident-prone areas. After that, the participants were asked to walk through a simulated scenario that shows subcontractors’ materials in the model. The purpose of this stage was to demonstrate to the participants the distinction between viewing a site layout plan in 2D drawings and viewing it in a VR interface. Following that, a simulated safe site scenario

was presented as a demonstration of the outcome of applied mitigation strategies that are found in the literature review where the participants could walk through a protected site model. This presentation of the safe scenario was aimed at providing the design engineers with an understanding of the implications of taking the precautions in terms of reducing hazards and emphasizing the significance of design engineer's expertise in achieving these outcomes. Guidelines from Safety-related toolboxes and regulations that were followed in the development of site simulations are described in the literature review. In the empirical part, these toolboxes are utilized to identify some hazardous points of the 6th floor of Kineum project and create a safer site scenario for the workshop. Finally, the participants were asked some reflection questions in order to collect the data regarding the participants' experiences and opinions of the activities.



Figure 01. Workshop activities flowchart.



Figure 02. Workshop set up with two VR headset users at the opposite ends of the room, a projector connected to one VR headset and a touchscreen board displayed in the middle of the room.

The workshop participants included two design engineers (civil structural engineers), a health and safety engineer, a head VDC developer (Virtual Design and Construction Specialist) and five researchers from different organizations (among them two serving as hosts and observers). The researchers were included with the aim to examine one of the study's core purposes, 'whether VR can serve as a valuable collaboration tool'. Names and designations of the participants are kept anonymous to protect the privacy and confidentiality of the participants. Table 01 provides a list of the participants and their roles during the workshop.

Table 01. List of the participants and their roles during the workshop.

Serial No.	Participants	Role during the workshop
01	Design Engineer 1 (Civil structural engineer)	Participant of all activities
02	Design Engineer 2 (Civil structural engineer)	Participant of all activities
03	Health and safety engineer	Participant of all activities
04	Lead VDC Developer (Virtual Design and Construction Specialist)	Participant of all activities
05	Researcher 1	Participant of all activities
06	Researcher 2	Participant of all activities
07	Researcher 3	Participant of all activities
08	Researcher 4	Host and observer of all activities
09	Researcher 5	Host and observer of all activities

During different parts of the workshop activities various data collection methods were employed, such as participant feedback, both predefined and open questions, observations, presentations, discussions, and recordings. All data was categorized and analyzed according to its content to derive relevant interpretations. The answers from the last session from participants' reflections on the workshop sessions were analyzed using the Likert scale and presented in diagrams to communicate findings effectively. All data collected during each session was utilized to derive the main results of the workshop. These results were then used to address the research questions and outline the key findings of the study. Finally, conclusions have been drawn and some suggestions for future study were made.

3. LITERATURE STUDY

This chapter describes the theoretical background related to improving safety on the construction site based on a literature review. The main topics covered in this literature study are VR and its implications in identifying hazards and facilitating collaboration, common accidents prevailing in the construction industry, the concept of “Prevention through Design and Tools” and regulations for hazard prevention. This chapter also includes a brief description of design engineers’ point of view for hazards recognition and safety planning. Facts and information provided are supported by reliable sources and references.

3.1 Implications of VR

This section briefly discusses the categories of VR, how VR is being used in the AEC (Architecture, engineering and construction) industry, its perceived advantages, and benefits in identifying potential risks and safety hazards, how multi-user VR facilitates collaboration, and some barriers that prevent its adoption in the AEC sector.

3.4.1 VR and its classification

According to Ozcan-Deniz (2019), an immersive VR is a computer-generated system of 3D images or environment that allows a certain level of interaction in a physical manner with the help of a Head Mounted Display (HMD), controllers/gloves with sensors, and a display screen. Applications of VR were first initiated within the gaming, marketing, and advertising area (Wolfartsberger, 2019). Wide use of VR in the gaming and entertainment industry has made this technology much more popular and cheaper. Nowadays, most tech companies, such as Facebook, Apple, Sony, Samsung, etc., have committed to investing in this technology in order to utilize the maximum potential that this technology offers (Syamimi et al., 2020). Currently, VR is being used for military training, automotive and aerospace design, medical training, entertainment, engineering education, construction hazard recognition, and construction safety promotion (Yan et al., 2022). In the AEC industry, integrated with BIM and game engines, VR is being used for design, visualization, management, and communication (Du et al., 2017).

Ozcan-Deniz (2019) categorized VR technologies into two main systems:

- Non-immersive or desktop-based VR requiring only a gaming laptop or PC.
- Immersive VR that involves HMD or goggles.

Again, Getuli et al. (2018) classified the applications of VR technologies to construction education and training into five categories (Table 02).

Table 02. Categories of VR technologies applied in construction education and training.

Categories	Features
Desktop-based VR	involves a desktop screen and the use of mouse and keyboard.
Immersive VR	involves the use of head-mounted displays and sensor gloves.
3D Game-Based VR	involves game-engine and offers multi-user operating technologies.
BIM-Enabled VR	uses BIM model to produce VR environment with all relevant building information and simulates construction process.
Augmented reality	uses special sensory technology.

Another type of immersive VR is CAVE Automatic Virtual Environment (CAVE) where large projection screens are used to create a spatially immersive display (SID) for the users to walk into the virtual environment (Ozcan-Deniz, 2019). Although there are different types of HMDs available, the HTC Vive and Oculus Rift are the most common types used in the industry today.

3.4.2 Uses and Benefits of VR in identifying potential hazards

Johansson and Roupé (2019) stated that affordable use of head-mounted displays (HMD) or VR headsets and widespread application of 3D design and modeling software like BIM have led to a greater adoption of VR in construction projects. The authors further pointed out that models designed in BIM including required 3D data can be directly extracted and applied to Virtual Reality that makes the VR technology easily applicable in the AEC industry. As such, BIM enabled VR is being used widely nowadays in the construction industry to develop immersive VR environments. For accurate simulation and analysis of the construction processes in the VR, a BIM model needs to be developed with high level of details and information in order to reduce data interoperability and it is recommended to use the IFC file format for transferring data from BIM to VR applications. (Getuli et al., 2018).

Getuli et al. (2018) identified using a BIM based VR provides several benefits, for example, with the help of a BIM model building geometry, data, and site phases can be accurately projected in the VR environment. Various VR systems can enable professionals in the industry to effortlessly enter, navigate and explore a building's virtual prototype which facilitates fundamental design communication and validation (Getuli et al., 2020). Ozcan-Deniz (2019) investigated 18 construction companies in the US to identify the main uses and benefits of VR. Analyzing 27 case studies of these companies the author highlighted that VR is primarily used for design reviews for clients and occupants and collecting their feedback, project coordination, monitoring the construction process and training of construction workers. Further benefits of VR identified by Ozcan-Deniz (2019) are improving communication and collaboration, lowering costs, and optimizing construction schedules, improving design reviews, improving training and safety, and improving construction site process through visual planning.

Because of the complexity and unique nature of construction site, safety management is more difficult and challenging compared to other industries. Guo et al. (2017) highlighted that visualization technology has the potential to aid in safety management as it increases job hazard area (JHA) identification and improves safety monitoring and safety training. The author referred

a job hazard area (JHA) to an area where there is a possibility of a potential job hazard, and it could be a potential source of collision, edges, openings, holes, or dangerous temporary structures. VR provides the opportunity to look through various cases of safety issues for a specific context of a unique project including different stages of construction processes (Sacks et al., 2015). Through visually experiencing the site, VR allows architects, designers, engineers, and construction professionals to identify possible hazards for a specific project even before the construction process initiates and facilitates taking accurate measures in the project planning phase (Azhar, 2017).

Effective application of VR for design reviews and flaw detection has been seen in the manufacturing industry. Wolfartsberger (2019) studied VR supported design review in an industrial set up to investigate its benefits compared to conventional design review approaches and found that VR based design reviews help identifying more faults than CAD based review on a computer screen. In the design review, the participants (16) of the study identified 30 of total 54 flaws through VR and 25 of total 54 flaws through CAD based approach. In this case, developed 2D layouts and 3D models viewed through PC screen cannot provide the impression of actual dimensions and scales as VR. Again, Wolfartsberger (2019) stated that since VR systems allow design reviews early in the design phase, it can provide faster entry into the review and can accelerate the design review process.

In terms of the construction industry, Zhou et al. (2012) stated that in a risk free and realistic virtual construction site, VR based DFSP (Design for safety process) tool can assist in identifying safety hazards that are produced during the design phase. In this respect, Guo et al. (2017) highlighted that visualization technology has been used to identify major types of hazards, such as accidents related to falling from heights, structural collapse, or collisions. Additionally, Sacks et al. (2015) pointed out that since VR provides in-depth understanding of hazards compared to construction drawings, some safety issues could be identified through VR which are almost unidentifiable by conventional methods.

Sacks et al. (2015) concluded that VR provides a better sense of scale, and the biggest advantage is that exposure to hazards can be experienced without any real danger. Studies of Chander et al. (2021) suggest that VR has the potential to be a useful tool for training in fall prevention by simulating high-altitude environments. Again, many design elements that are challenging to understand from conventional design documents, such as clashes and a lack of space for installations and maintenance, can be made clearer and identifiable using virtual reality (VR) system (Johansson & Roupé, 2019). More accuracy in material estimation and logistic planning becomes feasible with VR by its real-scale measurement and the capacity to plan the construction process ahead of time (Truong et al., 2021). All in all, the biggest advantage of using VR technology is that the learning curve is quick, and participants could easily use the system without difficulties (Ozcan-Deniz, 2019). Agreeing with this, Wolfartsberger (2019) argued that because of the immersive experience, VR requires a shorter training period to learn and use.

3.4.3 Multi-user VR as a collaborative platform

Due to the involvement of several actors during the design and production phases, effective collaboration is a prerequisite for proper planning of a construction project, and responsibility regarding safety planning to establish a decent and safe working environment should be taken by all actors (Swedish Work Environment Authority, 2022). Studies by Getuli et al. (2020) pointed out the need for solutions that would facilitate information sharing among project stakeholders due

to the complexity and fragmented nature of supply chains of construction projects. In this regard, VR can play a vital role by supporting collaboration between design teams and construction teams and facilitating a common understanding of design implications and safety issues (Sacks et al., 2015). Researching on the subject, Bassanino et al. (2010) acknowledged VR as a valid tool for supporting participatory design, as it can facilitate collaboration and communication among different stakeholders.

In the study conducted by Wolfartsberger (2019), the participants were asked to perform design reviews in a group where one person within the group was selected to wear and control VR headset, and other team members observed the stream VR view through a TV screen. After the test, the participants mentioned that the VR system should have a 'freeze' option so that the selected viewpoint could be discussed in detail and other observers can concentrate. Otherwise, observers cannot focus on a particular component as the screen is always in motion, leading to the person with the headset having to hold his/her head still in a point. Again, a few participants asked for features that could make all participants in the group visible in the VR model. The author highlighted that since design review is a collaborative process, in this case, single use VR isolates its user from other group members. The above-mentioned problems that the participants raised could potentially be solved by multi-user VR.

Collaborative multi-user VR sessions enables various stakeholders such as contractors, project managers, designers, engineers to virtually walk through a building design and discuss design requirements and solutions from different perspective (Getuli et al., 2018). Multi-user VR not only enables multidisciplinary collaboration which is a necessity for fragmented AEC industry, but also eases communication and enables faster and better design and construction process (Podkosova et al., 2022). Through a common virtual world, this ensures a common understanding between stakeholders which leads to a better work environment and safety performance.

Birt and Vasilevski (2021) investigated the usability of immersive virtual reality (IVR) and compared MUVR (Multi-user) and SUVR (Single user) in their use of experiencing BIM models. According to their study, MUVR significantly increases the overall perceived mobile IVR usability. Separating the non-immersive VR (2D monitors, CAVE etc.) from immersive VR, the authors mentioned three types of IVR- (i) mobile VR (Samsung Gear VR, Oculus Go/Quest), (ii) high-end heads mounted displays (HMD) (Oculus Rift, HTC VIVE) and, (iii) enhanced VR (often referred to as mixed reality using haptics and physical world data). Emphasizing the importance of collaborative participant discussion, communication, and interaction, Birt and Vasilevski (2021) mentioned that experience in MUVR was more engaging and significantly improves collective understanding and learning experience.

Again, outsourcing complicated design to international vendors and having project teams with diverse geo-location make remote communication highly characteristic of construction projects (Truong et al., 2021). In this respect, Du et al. (2018) proposed a cloud-based multiuser VR headset system called collaborative virtual reality (CoVR). In the case of BIM computer aided virtual environment (CAVE), users or the team members need to be physically present in the same location. However, CoVR uses cloud-based networking and BIM game engines to give project stakeholders who are located remotely a shared, immersive virtual experience via a cloud infrastructure, and users can communicate with each other through a real time voice tool (VOIP). Each user has access to an avatar that he/she can use to explore and move through the virtual environment and have face-to-face interactions. Therefore, in an interactive environment, it can facilitate interpersonal project communication and collaboration. The result of the study by Du et

al. (2018) indicated that with the help of CoVR, performance of building inspections is better than single user VR system and CoVR has the potential to create a shared vision for the project stakeholders before the production phase. Sateei et al. (2022) stated that multi-user VR promotes collaboration and reduces misunderstanding of design reviews by allowing its users to simultaneously explore same and different view-modes in the same model. Furthermore, Truong et al. (2021) investigated four real-life high-rise elevator projects from the user and business perspectives in a multi-user VR environment and discovered that it can greatly increase financial savings and gains for businesses in the construction industry by improving collaboration and coordination. Thus, multi-user VR has the potential to play a vital role in collaboration and communication for improved safety planning.

3.4.4 Challenges of VR adoption in the AEC industry

There are some challenges associated with this new and still immature technology. Ozcan-Deniz (2019) pointed out three main challenges of VR implementation. According to this paper, the challenges include the preparation of 3D models that require a high level of details, the requirement of multiple software applications and lack of streamlined software, and the lack of high degree of realism in the virtual model. Again, the interoperability between BIM and VR and conversion of data and reflecting real time changes of models in the VR is one of the main challenges of utilizing this technology (Podkosova et al., 2022).

In addition, the challenge is also caused by a lack of cost-benefit analysis and a knowledge gap between researchers and industry practitioners about VR (Truong et al., 2021). Moreover, for smaller companies, the initial cost of the necessary hardware, software, and staff training could seem expensive, however, the long-term savings of using VR technology can more than justify the expenditure (Ozcan-Deniz, 2019). Again, according to Ajslev and Nimb (2022), a lack of common standards, approaches, and unity impede the application and integration of this technology into improving occupational safety and health in construction projects. Furthermore, Azhar (2017) mentioned a lack of knowledge and training of S&H personnel and resistance to change are some of the barriers that hinder implementation of this technology into AEC industry.

3.2 Common accidents in the construction industry

Although the construction industry offers a lot of employment opportunities for workers, working in a construction site has always been dangerous to workers and caused several casualties all over the world (Yan et al., 2022). Accidents and occupational diseases are twice as common among construction workers as among other workers and the causes include falls from height, different types of load injuries and accidents when using different types of machines (Swedish Work Environment Authority, 2020). Zeng and Li (2022) mentioned that the most reported acute safety hazards were “workers fall from a height” and “electric shocks”. The authors associated this high level of injuries with noncompliance with fire and electrical safety requirements, a lack of discipline, and other causes. Zhou et al. (2012) pointed out the main causes of accidents involve falling from heights, being hit, or struck by a moving vehicle, being hit, or struck by a moving or falling object, or becoming trapped by something overturning or collapsing.

The German Social Accident Insurance shows that the most common causes of fatal accidents on German construction sites are caused by falls (30% of the accidents), vehicles and heavy equipment (13%), falling objects (8%) and accidents with tools and machines (6%) (DGUV,

2020). Again, according to the U.S. Bureau of Labor Statistics, falls account for 21% of all accident-causing factors, followed by accident-causing tools and substances (15%), falling objects (13%) and by heavy machinery and vehicles (8%) (OSHA, 2019). Therefore, based on data from the U.S. Bureau of Labor Statistics, German Social Accident Insurance, and the Swedish Work Environment Authority, a general trend can be seen and falls from height or fall hazards can be identified as the most common forms of accidents in the construction site.

In this respect, Occupational Safety & Health Administration (OSHA) states that falls are the leading cause of death in the construction sector in the US and falls cause one of every three construction worker deaths (OSHA, n.d.). At a construction site, major types of fall hazards include unprotected roof edges, roof and floor openings, structural steel, and leading edges; improper scaffold construction, and unsafe portable ladders (OSHA Training Institute, 2011). In this research, only fall hazards caused by unprotected floor openings will be focused on in our further investigation.

In a prevention video developed by OSHA, it was explained how various types of accidents related to openings can happen while workers work on heights, roofs, and other work surfaces (USDDepartmentofLabor, 2011). One example was given when two workers were framing the walls on the second floor near a stairwell opening. The opening was not protected by a guardrail or floor cover and the workers were not wearing personal fall protection. While moving with the frame one of the workers fell 20 feet (approximately 7 meters) down through the unguarded stairwell opening and died from fatal head and internal injuries. These types of accidents are common in the construction industry, and OSHA claims that all these can be prevented through proper protective measures. Although human error or individual recklessness are typically blamed for accidents, in a dangerous and complex environment like a construction site, there may be several interrelated elements that can contribute to risks or accidents (Zhou et al., 2012). Therefore, it is crucial to identify the source of these kinds of hazardous or risky areas before the construction work initiates, so that the appropriate precautions can be taken during the planning and design phase.

3.3 Prevention through Design

The construction industry is globally characterized by different levels of occupational health and safety performance. Although in developing countries this range of safety is higher than in developed countries, the increasing focus on occupational health and safety is encouraging and has the potential to lead to significant improvements in the safety and well-being of construction workers around the world (Che Ibrahim et al., 2022). Implementing risk management, choosing the right designers and organizations, and giving information, teaching, training, and supervision about occupational health and safety (OHS) are some of the most important parts of 'Prevention through Design' (PtD) principles (Manu et al., 2021). The idea behind 'Prevention through Design' is to lower the possibility of workplace incidents by adding safety precautions during the design phase. Keeping risks and dangers to a minimum means making sure that systems, processes, and goods are made with safety in mind from the beginning (Martinez Aires et al., 2010). In the following subsections, some tools that can be useful to adopt 'prevention through design' and the existing regulations for safety regarding fall hazards are briefly described.

3.3.1 Tools

Integrating safety and health concerns early in the design process is known as "Prevention through Design" (PtD). Tools, both software and hardware, can help with tasks, especially risk assessment and hazard identification (Che Ibrahim et al., 2022). In this subchapter, three tools are described which can be useful for design engineers to address and evaluate construction safety during the early phase. These three tools were chosen to develop a comprehensive safety suggestion list out of several alternatives. Selected two tools- (CII) IR101-2 and SlideRuLe were developed by reputable organization like CII tested and refined through extensive research and industry use. All three tools are aligned with industry standards and best practices, which make them easier to integrate into existing project workflows. Lastly, these tools like SliDeRule and CII's offerings tend to cover a wide range of potential hazards and risks, providing a comprehensive framework for risk assessment and mitigation which will be described in the following paragraphs. Since this study focuses on fall hazards especially related to floor openings as mentioned in the previous section, safety suggestions and recommendations from these tools are described only regarding unprotected openings.

- CII- Design for Construction Safety Toolbox (Gambatese et al., 1997, Ku K., 2014; Gambatese J., N. C. (2015); Gambatese & Hinze, 1999)
- SlideRuLe- Safety in Design Risk Evaluator (Dharmapalan et al., 2015; Gambatese J., 2015; Jin et al., 2019).
- Sothern Company's Design for Safety checklist (Aycock J. et al., 2011; Speegle, A., n.d.).

Table 03. Classification of the three tools by different categories.

	Purpose and Function	Stage	Suggestions Number	Used Resources	Building Systems/Topic
(CII) IR101-2	Evaluate, and mitigate construction safety risks during the project's design phase	Design stage (all project stages)	400	Safety design manuals, checklists, and ideas generated by both researchers and CII Research Team members. Additionally, interviews with industry personnel, OSHA (Code of Federal Regulations), journal articles, periodicals, public safety courses, and other resources including NIOSH (National Institute of Occupational Safety and Health) or HBR (Houston Business Roundtable) Constructability Plan were consulted	Administrative: Layout, Administrative: Planning, Administrative: Design, Sitework: Layout, Sitework: Roads/Paving, Sitework: Earthwork, Foundation, Roofing, Structural: Steel, Structural: Concrete, Structural: Masonry, Structural: Timber/Wood, Finishes: General, Finishes: Stairs/Railings, Finishes: Ladders, Doors & Windows, Mechanical & HVAC, Electrical, Industrial Piping, Tanks & Vessels
SlideRuLe	Assist building designers in assessing the safety risks associated with their designs during the construction process	Design	n.d.	Survey-analytical approach to gather data from construction workers and design professionals	Foundation, Structural Frame, Exterior Enclosure, Roof, Interiors, Fire Suppression, Plumbing, HVAC, Electrical
Sothern Company's DFS checklist	Identify and address potential safety hazards that may arise during construction projects	Design & Construction	1654	Collaboration between Southern Company and other US-based companies, with input from industry professionals including Alan Speegle, Tom Bullington, Rick Callor, and David Engdahl, who each provided safety-related suggestions and served as primary contacts for their respective areas of expertise	Architectural, Ammonia, Barricades&Signs, Building exterior, Building Interior, Buildings, Civil, Concrete, Construction, Contract drawings, Constrol system, electrical, Environmental health, existing buildings, Fiberglass, Furnishing & Equipment, General, Handrail & Guardrail, I&C, Lighting, Mechanical, Piping, Plot plan, Procurement and Contracting, Protective Coating, Road and Parking, Stairs, Steel, Systems, Tank & Vessels

CII (Construction Industry Institute) Designing for Construction Safety Toolbox

Definition of CII Toolbox. Construction Industry Institute (CII) IR101-2 is called a "Designing for Construction Safety Toolbox" which offers guidance on designing for construction safety by providing tools and techniques to assess, evaluate, and mitigate construction safety risks during the project's design phase (Construction Institute (CII), n.d.). Ku K. (2014) pointed out that the construction industry does not have adequate design support tools to identify and control hazards during the early stages of design and planning. However, CII IR101-2, Design for Construction Safety Toolbox, uses text-based checklists that can be accessed through paper or software interfaces and applied manually to design drawings or construction documentation in the field, such as on tablet computers. By using these tools, construction professionals can ensure that safety considerations are integrated into the design and planning process, ultimately leading to safer construction sites (Ku K., 2014).

Use stage of CII Toolbox. The program provides prescriptive suggestions, which are commonly known as "best practices," to mitigate or eliminate safety hazards, prevent injuries and associated costs, and foster positive project outcomes. Its usefulness is particularly evident during the preliminary stages of the design phase, as it covers all project stages and is applicable to construction projects of various scopes and sizes (Gambatese J., 2015).

Used Sources for CII Toolbox. Subsequently, the 400 design suggestions were collated and integrated into the design tool database. The sources for these design suggestions comprised various references such as safety design manuals, checklists, and ideas generated by both researchers and CII Research Team members. Additionally, interviews with industry personnel, OSHA (Code of Federal Regulations), journal articles, periodicals, public safety courses, and other resources including NIOSH (National Institute of Occupational Safety and Health) or HBR (Houston Business Roundtable) Constructability Plan were consulted (Gambatese et al., 1997).

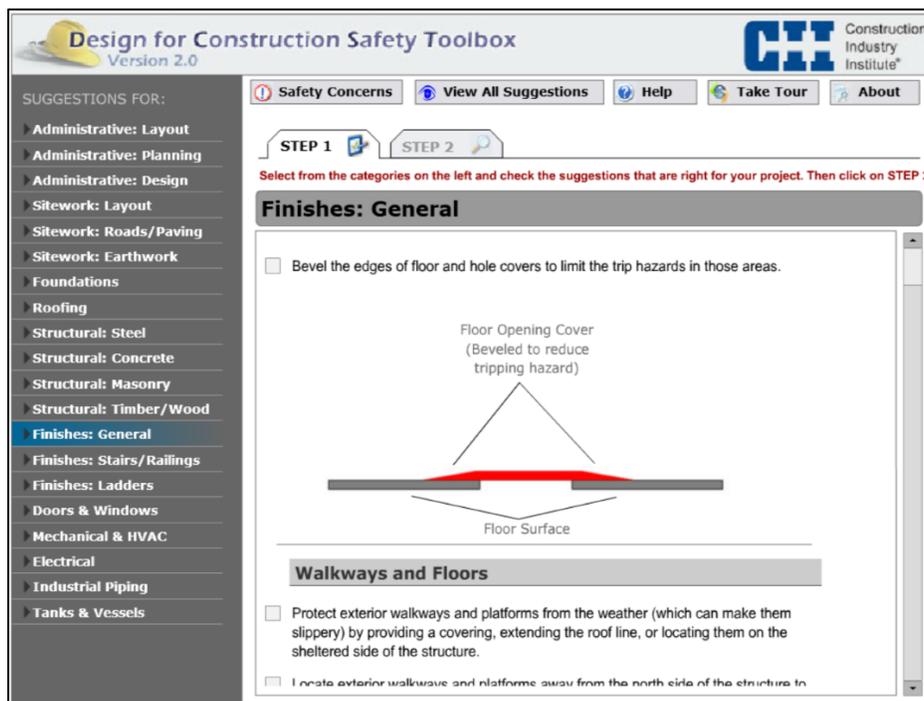


Figure 03. An interface of the CII Design for Construction Safety ToolBox.

Limitation. The toolbox is mainly designed to address safety concerns that arise during the initial stages of construction projects. However, the toolbox might not encompass all facets of construction safety, such as operational safety or maintenance-related safety matters.

Openings in the CII Toolbox. In the CII Design for Building Safety Toolbox, different safety suggestions are under different categories of building components which were sorted regarding openings. These sorted categories are listed in table 04.

Table 04. Sorted building components/subcomponents from the CII Toolbox related to openings.

Categories	Subcategories
Foundations	Concrete slabs and concrete floor surfaces
Roofing	Roof openings, Added Features
Structural: Steel	Beams and Columns
Structural: Concrete	Fall Protection
Structural: Timber / Wood	Fall Protection

As per CII recommendations, it is advisable to have permanent guardrails installed around floor openings for concrete slabs. Furthermore, steps, curbs, and slab depressions should be kept away from window openings, exterior edges, and floor openings to avoid tripping hazards. It is also important to include warnings in the construction plans and specifications for design features that cause floor openings, such as ventilation systems, trash chutes, elevators, etc. Moreover, it is recommended that permanent guardrail systems be designed and installed early in the construction process to be used by all contractors. For the structural part, perimeter beams and beams above floor openings should be designed to support lifelines with a minimum dead load of 5400 lbs (about 2449.4 kg). The connection points along the beams should be designed for the lifelines, and it should be noted on the contract drawings which beams are designed to support lifelines, how many lifelines there are, and at what locations along the beams. These safety measures can help prevent accidents and ensure a safe construction site for workers.

SlideRuLe (Safety in Design Risk Evaluator)

Definition of the SlideRuLe. Safety in Design Risk Evaluator (SliDeRule), available at www.constructionsliderule.org, is another tool developed by the Construction Industry Institute (CII) with the same goal as the previous tool: enhancing safety in construction projects (SliDeRule., n.d.). Dharmapalan et al. (2015), authored by the developers and contributors of SlideRuLe, described the tool as an online tool designed to assess the safety risks of construction designs. It offers users the ability to input information regarding various design elements, allowing for comparisons and modifications based on associated safety risks. Additionally, SlideRuLe provides specific examples of design features that can either enhance or impede the safety of construction workers.

In order to determine the safety risk values associated with each design, it is required to calculate the quantities of materials by given units and then input these values into SliDeRule. For example, as shown in Table 05, due to the higher risk associated with the application of the modified bitumen coating, the result indicated that membrane roofing carries a lesser safety risk value than modified bitumen membranes (Gambatese J., 2015).

Use Stage of the SlideRule. According to Dharmapalan et al. (2015), the website's purpose is to aid building designers in evaluating the degree of risk associated with their designs in terms of construction safety. It is specifically intended to be utilized by designers in the design phase of the building process to produce structures that prioritize safety during the construction process.

Used Sources of the SlideRule. The study employed a survey-analytical approach to achieve its research objectives, which involves gathering data from construction workers and design professionals. The main aim of this approach was to identify common building design elements, construction activities, and the associated safety risks. To accomplish this, the researchers developed survey questionnaires to cover various aspects of building construction, such as structural framing, roofing, and exterior enclosure, as well as different construction professions (Dharmapalan et al., 2015).

Table 05. Review of As-Built and Alternative Roofing Systems (SliDeRule., n.d.)

Design	Design Element	Cumulative Risk Factor (Severity/SF)	Quantity	Total Design Risk
As-built	Single-ply (PVC) membrane roofing over metal deck	0.0003	6,159 SF	1.9
	Single-ply (PVC) membrane roofing over concrete deck	0.0019	3,800 SF	7.2
Alternative	Modified bitumen roof membrane over steel deck	0.0045	6,159 SF	27.7
	Modified bitumen roof membrane over concrete deck	0.0072	3,800 SF	27.4

Limitation of the SlideRule. The limitation of the SliDeRule tool is that it currently is limited to design elements for multistory buildings. The risk factors of the design components must be quantified and included to achieve an accurate risk score. Additionally, if design elements are constructed using different methods or equipment, in that case, which method was used to develop the risk scores in SliDeRule is not certain, therefore, the identified risk scores may not be accurate. Lastly, SliDeRule does not emphasize any particular risk related to building or creating a design element, such as the danger of working at an elevated height. As a result, potential hazards may not be adequately identified or highlighted by the tool (Jin et al., 2019). Dharmapalan et al. (2015) noted that further investigations are required to identify the design-related hazards associated with various types of projects, including but not limited to roadway, bridge, industrial, and light residential projects, as the current research predominantly focuses on multistory buildings.

Openings in the SlideRule. The primary focus of SlideRule is around the analysis of potential hazards through an assessment of design choices, solutions, material selection, and installations, among other pertinent factors. This tool counts every action as a risk for workers because the construction site is a risky place, even installations of safety objects have several rates of risk according to several methods of installation.

When using the SliDeRule tool to assess risk scores, the installation of safety measures such as fall protection may result in a higher cumulative risk score compared to a design without safety considerations. For instance, a design with a guardrail may receive a higher risk score than one without due to the inclusion of the risk associated with installing the fall protection measure in the cumulative score. Therefore, it is crucial for design professionals to be mindful of this scenario and make informed decisions when selecting design elements and making modifications (Jin et al., 2019).

Sothern Company's Design for Safety checklist

Southern Company has developed a comprehensive Design for Safety (DfS) checklist that represents the most important or relevant safety-related aspects within the four main design disciplines, namely Civil/Structural, Mechanical/Piping, Electrical, and Instrumentation and Controls (Aycock J. et al., 2011). It includes 1654 safety issues that may arise during construction projects.

This particular checklist is designed in a table format, with several headings that provide important information about each task. In addition to some columns, like ID, title, and contact person of potential hazards, this checklist features several other columns that provide additional information about each task. The engineering discipline column specifies the type of engineering required to complete the task, such as civil or mechanical engineering, while the system or topic column identifies the area of the project to which the task pertains, such as handrails or piping.

Use Stage of the DfS Checklist. The department column indicates which department is responsible for completing the task, such as design or construction, and the entry category column specifies the type of issue the task pertains to, such as safety or quality. These additional columns are crucial in helping to identify specific cases easily. The final columns are Description and Resolution which include a description of any potential safety issues that may arise during the completion of the task and the proposed resolution for these issues (Speegle, A., n.d.).

Limitations of the DFS Checklist. This extensive checklist, which is classified into various subheadings, provides comprehensive information on each task related to the construction project to ensure timely and effective resolution of any potential safety concerns. As it comprises input from multiple companies, the data presented is limited to sector-specific insights, which makes it challenging to obtain more academically rigorous resources.

Used Source for the DfS Checklist. Through collaborations between Southern Company and various companies in the United States, a checklist has been developed by leveraging the collective expertise and experience of industry professionals. These professionals are Alan Speegle from Southern Company, Tom Bullington from KBR, Rick Callor from Washington Group, and David Engdahl from Haskell, who serve as the primary contact for their respective safety-related suggestions (Speegle, A., n.d.).

Openings in the DfS Checklist. The safety concerns associated with openings from the DfS Checklist of Southern Company are sorted and presented in their entirety in Table 06.

Table 06. Sorted safety issues from Southern Company's DfS Checklist related to openings.

ID	Title	Engineering Discipline	System/Topic	Department	Entry Category	Description	Resolution	Point of Contact
400	Floor Plan	Civil	General Arrangement/Project Layout	Design	Safety	A building's floor plan can lead to fall hazards if there are numerous offsets of varying size, floor levels varying in size or shape, or if the size and layout does not meet local building codes.	Locate floor openings away from passageways, work areas, and the structure perimeter.	Alan Speegle (Southern Co.)
547	Miscellaneous Steel, Railing and Grating	Civil	Structural Steel Framing	Design	Safety	Structural steel erection operations can lead to collapse if adequate support is not provided for the members before permanent connection. Welding operations can create fire hazards due to excessive slag or sparks, and also expose construction workers to	Grating with pre-cut openings should have temporary plywood covers tied over them, using proper gage wire, until the openings can be secured with handrails, hatches, etc. Install the plywood covers in the shop or on the ground at the plant construction s	Alan Speegle (Southern Co.)
832	Elevated Floor Concrete	Civil	Concrete	Design	Safety	Concrete: Elevated Floor Concrete	Consider using bent steel form plate on elevated floor slabs around the edge of concrete at large openings and around the perimeter.	Alan Speegle (Southern Co.)
1663	Floor opening	Architectural	Building interior	Design	Safety	Fall from elevation	Provide permanent guardrails.	Washington Group (Rick Callor) Haskell (David Engdahl)
1664	Flooring in wet areas (exterior tile, wash down areas, kitchens, etc.)	Architectural	General	Design	Safety	Slipping	Provide slip resistant floor materials.	Washington Group (Rick Callor) Haskell (David Engdahl)
1761	Falls From Elevation	Civil	Structural - construction	Construction	Safety	Slab openings/edges provide potential for workers to fall through	Provide requisite guardrails and toe boards at all slab openings/edges	Washington Group (Rick Callor) Haskell (David Engdahl)

3.3.2 Regulations

To adopt and implement prevention through design it is important to be aware of the existing rules and regulations regarding construction safety. Since this study focuses on fall hazards related to openings, existing safety regulations to prevent this type of hazards are briefly described in this section.

As our study is limited on a case study in Sweden, regulations according to Swedish Work Environment Authority (2022) is reviewed in this section. The organization suggests that if there is a risk of falls from 2 meters during building and construction work, regulations must be followed, otherwise sanction fees will be charged. In respect to working at a height or if the construction workers are exposed to risks of fall hazards, employers should take proper responsibility to provide required safety precautions. According to the Swedish Work Environment Authority (2022),

- Fall protection should be provided by using Guardrail, Work platform, Work basket, Scaffolding, Safety net and personal fall protection equipment.
- Fall protection guardrail or other safety barrier must be installed over openings and holes where there is a possibility of height falls.
- Guardrails or safety barriers need to be at least one meter high and around the whole opening.
- Strong and reliable barriers must be used to block off any areas where there is a possibility of falling through a roof.

3.4 Design engineers' point of view

According to Swedish Work Environment Authority (n.d.), the Work Environment Act 2018 states that every actor who are involved in a construction project should take the responsibility to provide a safe working environment. The regulation states as

“Chapter 3: General regulations 7 § During each stage of the planning and design of a building or construction work, architects, designers and others who participate, within the scope of their assignments, must ensure that work environment considerations are taken into account both in the construction stage and in future use.”

Responsibility- Design engineers are not aware of their responsibility

In the Health and Safety section of the construction industry report, Brace et al. (2009) summarized the underlying factors contributing to serious accidents in the construction industry, which were grouped into three themes: macro, mezzo, and micro. The macro factors, such as society, education, industry, corporate organization, and unions, have a significant and direct influence on the other two categories, which also shape the safety culture in the construction industry. Inadequate business processes, incorrect enforcement, insufficient accident data, government leadership, and trade union influence are examples of macro-level problems. Additionally, mezzo factors include inadequate project systems, procurement, supply chain arrangements, design community engagement, and inadequate accident investigation. Addressing the issues at the macro and mezzo level can result in better safety outcomes at the micro levels which consist of a shortage of competent supervisors, inadequate individual competence, ineffective training, and lack of ownership, engagement, and responsibility. The designers, who are part of the mezzo factors, play

a crucial role in ensuring safety in the construction industry. They can use their expertise to identify and mitigate potential safety risks in construction projects. Therefore, addressing the issues at the mezzo level, including the role of designers, can lead to better safety outcomes in the construction industry (Brace et al., 2009). However, Gambatese and Hinze (1999) emphasized that although being a crucial party, designers are still left out from participating in safety considerations of their projects. Safety is often neglected until construction begins, disregarding the significant impact that designers have on construction workers' safety. The design dictates the appearance and assembly of a project, and designers greatly influence decisions on construction tasks. Therefore, it is vital that designers recognize their influence and take responsibility for promoting construction safety (Gambatese & Hinze, 1999). Sacks et al. (2015) mentioned that designers prioritize eliminating hazards to building occupants but may not extend the same level of concern to the construction process. The researchers aimed to test designers' knowledge and attitudes toward construction safety hazards and explore the efficacy of design reviews for construction safety conducted by designers and construction professionals. The authors contend that designers could increasingly consider safety when selecting design solutions. However, Gambatese (2000) discovered that designers often focus on the safety of building occupants rather than construction workers.

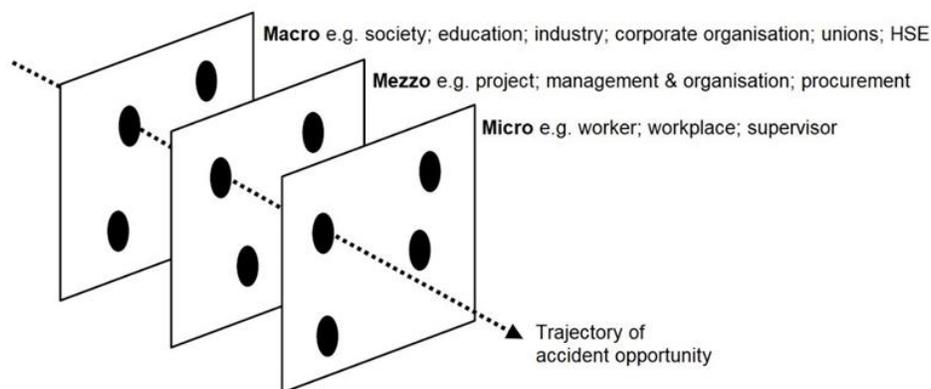


Figure 04. Factors contributing to serious accidents in the construction industry (Brace et al., 2009).

Design changes can create significant difficulties in planning safe work, especially when working at heights or lifting heavy elements, as well as in renovating or demolishing old structures. Therefore, to play a useful role, designers must acquire knowledge and understanding of how health and safety risks and hazards in construction arise and how design can prevent or minimize them. Shrestha et al. (2022) listed the duties of designers related to health and safety on construction sites, which include ensuring their own competence, preparing method statements, providing information about hazards and risks associated with their design, considering how maintenance will be carried out safely, coordinating with other designers and contractors to ensure safety during construction work. In the study, the duties were compiled based on existing regulations and best practices and were analyzed according to designers' and contractors' levels of agreement. Some respondents strongly agreed with these duties, while others may have had reservations or disagreed with some aspects. This suggests a lack of uniformity in how designers and other professionals perceive their responsibilities for ensuring health and safety on construction sites, which could lead to confusion or inconsistencies in practice (Shrestha et al.,

2022). In this regard, Hinze and Wiegand (1992) conducted a survey among design firms in the US to determine which firms integrate safety for construction workers into their design process. The results of the survey indicated that only seven out of twenty-three firms that responded implemented design decisions specifically intended to enhance construction worker safety, while some firms did not even consider safety at all. One of the respondents expressed concerns that getting involved in worker safety could result in legal liability and expose them to potential litigation in case a worker is injured. This implies that certain firms may prioritize avoiding legal responsibility over proactively considering and addressing safety concerns for construction workers during the design phase (Hinze & Wiegand, 1992).

Accountability- The way to make design engineers feel responsible

Brace et al. (2009) explained that the design community's leaders are making commendable efforts towards enhancing the health and safety of construction workers by using Construction Design and Management Regulations (CDM). However, the study revealed that many designers hold the belief that safety measures are not their responsibility. Few designers who wish to participate are encountering difficulties because they lack knowledge of good practices, and express confusion by stating 'does it really apply to me?' (Brace et al., 2009). Gambatese and Hinze (1999) mentioned that in Great Britain, the CDM Regulations entail the participation of designers in the identification and mitigation of health and safety hazards present in construction projects. The authors state that "while designer involvement in construction worker safety in the U.S. is voluntary, the CDM Regulations are mandatory". As another step for addressing workers' safety, this study developed software for identifying "project-specific hazards", which helps in/to complete the mandate of CDM Regulations (Gambatese & Hinze, 1999). Bong et al. (2015) explained that design firms can play a critical role in creating a culture of safety that prioritizes the safety of workers by adopting safety guidelines and integrating them into their design process while working together with procurement and contracting systems. Conversely, designers face a challenge in implementing a safety solution if its cost is not accepted as part of the overall life cycle cost structure by the client. Sacks et al. (2015) also mentioned that designers' legal responsibilities play a vital role in shaping the way construction safety is approached and viewed.

According to McAleenan and Oloke (2015), the concept of **prevention through design (PtD)** allows companies to remove various sources of hazards associated with construction before the actual construction phase. While innovative practices can be developed to promote a safer and healthier future for the industry, PtD can also provide design firms with a long-term competitive benefit. The authors further stated that recently health and safety have been viewed as a means for designers to explore their creativity.

Sacks et al. (2015) stressed the importance of having safety education and training for designers in construction safety. They added that to ensure their designs are safe and efficient, designers must have knowledge about possible hazards present on the site and an opportunity to conduct early reviews of their designs. According to Brace et al. (2009), accidents can be attributed to the lack of individual competency among managers, supervisors, and workers. In the study, 'competency' is discussed in terms of both knowledge and technical ability, as well as more significantly softer issues such as an engaged attitude. This lack of competency among managers and workers is a result of insufficient training provided to industry members, which can lead to several issues such as inadequate risk assessment, poor planning, and a lack of good practice. The authors suggested that professionals in the construction industry, particularly designers, do not see health and safety as an integral part of their job. In this respect, however, there are many safety-

based organizations and agencies around the world that focus on the training of design managers, employees, and workers for safe work practices and continuous improvement (SafetyWorks-Maine Department of Labor, n.d.). For example, Occupational Safety and Health Administration (OSHA) grants are available to educate workers and small business employers about new OSHA standards, as well as high-risk activities or hazards. The grantees are also required to follow up with those who have been trained to determine what measures were taken to reduce hazards in their workplaces. OSHA Training Institute encompasses a wide range of subjects related to safety and health, like "electrical hazards, machine guarding, personal protective equipment, ventilation, and ergonomics" (Occupational Safety and Health Administration, 2002).

4. EMPIRICAL STUDY

This chapter begins with a brief introduction of the project and the case that was chosen for the case study. Following that the chapter describes the process of preparing the scenarios for VR walk throughs and tools and features that can be used with VR headsets and controllers. The chapter ends with the description of each activity including exercises and discussions that were conducted during the workshop.

4.1 Description of the case project and case study

The case study for the thesis is the Kineum project, which was a significant construction, consisting of a 42,000 square-meter existing building and a new 27-story tall building. The building has an innovative design and contains offices, a hotel, meeting spaces, and services (NCC, 2021). The project is a collaborative effort between NCC, Platzer, and tenants, creating a landmark in Gothenburg that promotes innovation, new thinking, and creativity (NCC, n.d.a).

Facts. The Kineum project, undertaken by NCC Building for Gårdabolaget AB, involved the construction of a large-scale office building spanning over 30,000 square meters. The office space is in the same building as ESS Group's newest hotel, Jacy'z, and was completed between 2019 and 2022. The project was carried out as a turnkey contract in collaboration with the client. One noteworthy aspect of the Kineum project is its focus on sustainability, as evidenced by the building's environmental certification under the BREEAM standard. This certification serves as a testament to NCC Building's commitment to incorporating sustainable practices into its construction projects (NCC, n.d.b).

Challenges. The Kineum project is located in Gårda, Göteborg, with a complicated foundation due to various factors, including the existence of a building, the Platzer scraper, adjacent to the workspace, the impact on existing piles from two directions, an extremely small footprint, sluggish mud, and concentrated loads. Furthermore, the project had to take into account environmental impact, such as vibrations and noise, due to the high-density office areas in Gårda. The casting of pile foundations and base plates was another critical aspect of the Kineum project. The project faced challenges in keeping up the pace of casting due to rush hour traffic and the limited work surface that did not allow for climbing shape. Hence, sliding mold casting was chosen, which is a complex technology that required self-made wooden scraps, welding plates, and a significant amount of reinforcement. Finally, the project had to adapt the design of the elevator core to fit the sliding shape method, and the elevator shaft was cast first before lifting in stairs and joists, followed by the frame and facade using a tower crane (NCC, n.d.b).

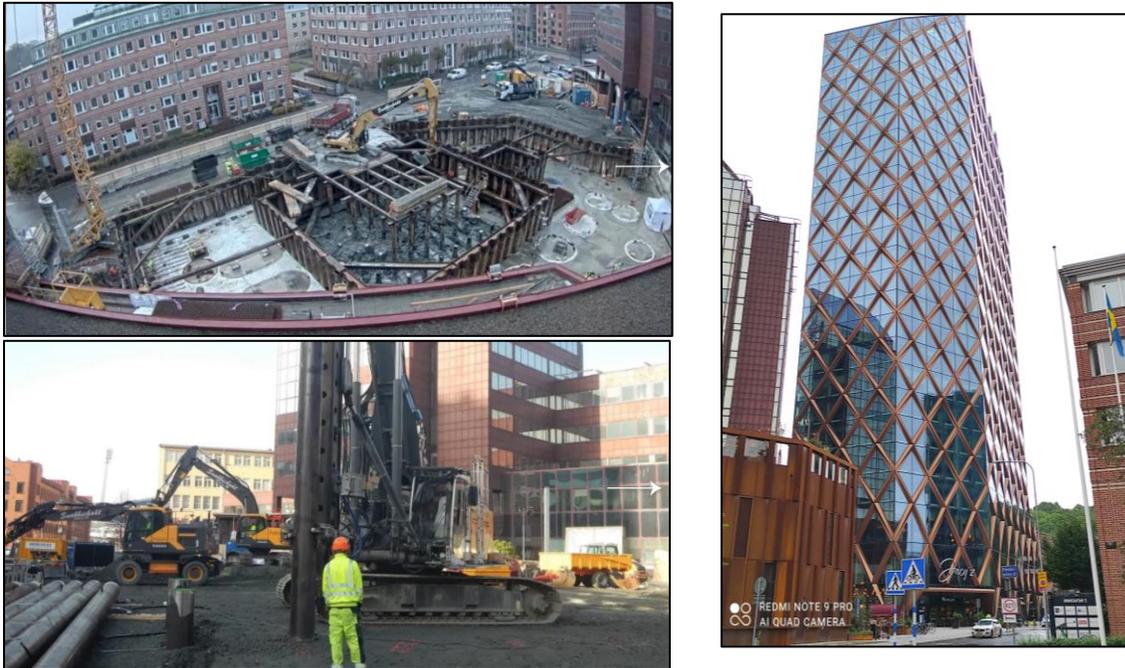


Figure 05. Kineum project. Left: Construction site (NCC, n.d.b); Right: Street view.

Potential fall hazard situations reported during the construction. Since the literature review suggested fall hazards are the highest in terms of accidents in the construction industry, the accident reports (Arbetsmiljöincident, 2023) which were recorded during the construction process of the Kineum project, were investigated to identify incidents that could have been caused fall hazards. A few incidents were pinpointed that could have possibly resulted in fall hazards. The identified incidents are-

- working at a high altitude without safety equipment (2022-09-09; 13:13)
- unauthorized rolling stand with no guardrails (2022-08-03; 10:58)
- large openings in the façade without screwed protective railings (2022-05-30; 12:29)



Figure 06. (a) unauthorized rolling stand with no guardrails; (b) large openings in the façade without screwed protective railings (Arbetsmiljöincident, 2023).

Case description. These reported incidents could lead to a potential fall hazard, hence, to examine if this type of hazardous area can be identified by VR, a walkthrough BIM model of Kineum project was simulated with BIM components to create a virtual construction site. Due to time limitation, a single floor was chosen to simulate instead of the whole building. The building's 5th to 8th floor work as NCC's offices and the rest of the floors serve as offices, hotels, and restaurants. To reduce complexity, only the 6th floor was chosen to simulate and prepare for VR walkthrough.

4.2 Preparation of Scenarios for a VR walkthrough

Since conducting a workshop was chosen for the empirical study, three scenarios were decided to be simulated in the VR walkthroughs during the workshop: an unsafe scenario, a scenario with different subcontractors' materials imitating the 2D site layout plan, and a safe scenario with protective equipment such as guardrails, covers, bands etc. All three scenarios were created in the software BIMXplorer V1.7.5. Several BIM components were needed for creating relevant scenarios.

4.2.1 BIMXplorer

Preparing BIM components for BIMXplorer.

The process of creating the VR environment in this study needed some laborious tasks and numerous file conversions. To prepare the site scenarios, several BIM objects related to safety were collected from different website libraries and put into a Revit project. Some of the BIM objects related to safety were not readily available. For those objects, files were created through ArchiCAD, SketchUp and 3D Max, and edited by applying materials, scale, color to the objects. These objects were imported in Revit so that all objects can be arranged in a single project. The Revit model with all the BIM objects was then uploaded to BIMXplorer. In the BIMXplorer, each BIM object was selected and isolated to hide all other objects to use as a single, independent object. After isolating, a thumbnail was created for the object which can be renamed. All the objects were categorized in this process according to the purpose of the object such as lighting equipment, guardrails, heavy vehicles, warning signs, cranes etc. All the objects are saved in the hardware and can be imported into the BIMXplorer.

BIMXplorer in a Touchscreen board interface.

The simulation for preparing the virtual site scenario was done in BIMXplorer in a touchscreen board interface which had 65" screen. The model of the touchscreen board that was used to open the BIMXplorer file was 'BENQ interactive touch panel'. The touchscreen board interface allows to drag the BIM components and set them in the model with proper alignment. The prepared BIM model in the BIMXplorer then can be viewed in the VR environment with the help of VR headsets and controllers. With the help of a touchscreen board, BIM models can be viewed and saved BIM objects can be used to modify and update the BIM model. Changes and modifications made in the model through touchscreen board are instantly visible in the VR HMD.

Main features of BIMXplorer used for the simulation.

The ***filtering tool*** in this application allows users to selectively hide various objects or components based on their properties within the BIM model. For instance, it is possible to hide all walls collectively by specifying the property name, such as "wall," or hide a specific wall by entering its schedule code.

One of the frequently utilized features in this application is **importing or adding prefabs** for different scenarios. BIM components that have been prepared beforehand are saved as prefabs in the BIMXplorer. To include them in a scenario, users need to load them from the folder (Figure 07). Scenarios that are created using these prefabs are required to be saved in two different ways: firstly, by saving the prefabs as a vicode (vcd) file (Figure 08); secondly, by saving the entire model as a BIMXplorer (bimx) file. Saving prefabs separately is advantageous for reusing the same prefab furnishings in another project or utilizing different groups of prefab placements at different times. For instance, on one floor, construction vehicles, and containers are placed. They can be saved as separate groups, such as "containers" and "construction vehicles," and loaded individually using the "**add prefab file**" function (Figure 08).

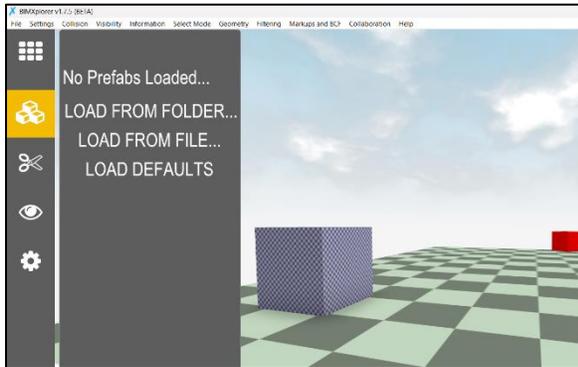


Figure 07. Importing prefabs in BIMXplorer.

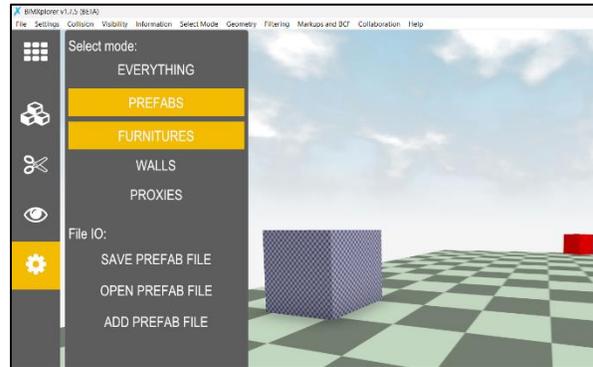


Figure 08. Saving prefabs in BIMXplorer.

4.2.2 Three site scenarios

Since the plan of 6th floor of Kineum project was chosen for our cases study, using the features and options of BIMXplorer and the BIM objects/components, the 6th floor of the BIM model of the project were adjusted. Through this, three simulated construction site scenarios were developed.



Figure 09. Three scenarios developed in BIMXplorer.

- **Unsafe scenario:** The unsafe scenario involves a specific time period characterized by the start of architectural construction after the completion of structural construction. For this unsafe scenario, it is assumed that the structural aspects of the project are almost finished, and there are non-structural walls, doors, furnishings, MEP components, or finishing works. To create this scenario, certain objects in the 3D model were intentionally hidden. This was achieved by filtering approximately 72 elements based on their descriptions, type

name, object class, and schedule code using BIMXplorer 1.7.5 (Figure 10). Additionally, to make the site more unsafe in terms of openings, no safety precaution components were set in the model, and objects were placed on the 6th floor, increasing the potential hazards.

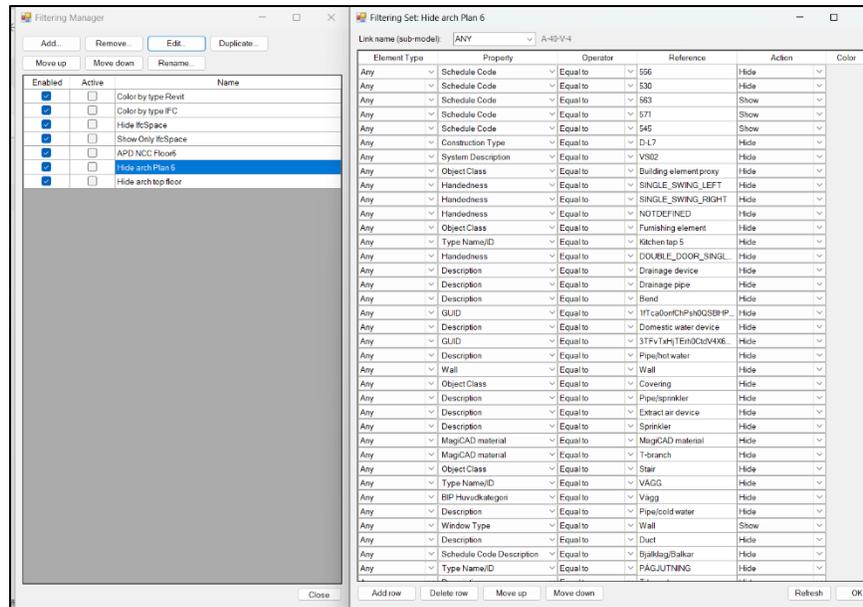


Figure 10. Filtering set: hiding architecture file in BIMXplorer.

- Scenario with different subcontractors' materials imitating the 2D site layout plan:** The simulation for this scenario was done imitating a 2D site layout plan of the 6th floor of Kineum Project (May 2021). The 2D site layout plan of the 6th floor depicted the areas of different subcontractors such as painters, ventilation, electricity etc. In the BIM model, the BIM components such as painting equipment, ventilation equipment, electrical equipment were set up at the same area following the 2D site layout to create the simulated site scenario.

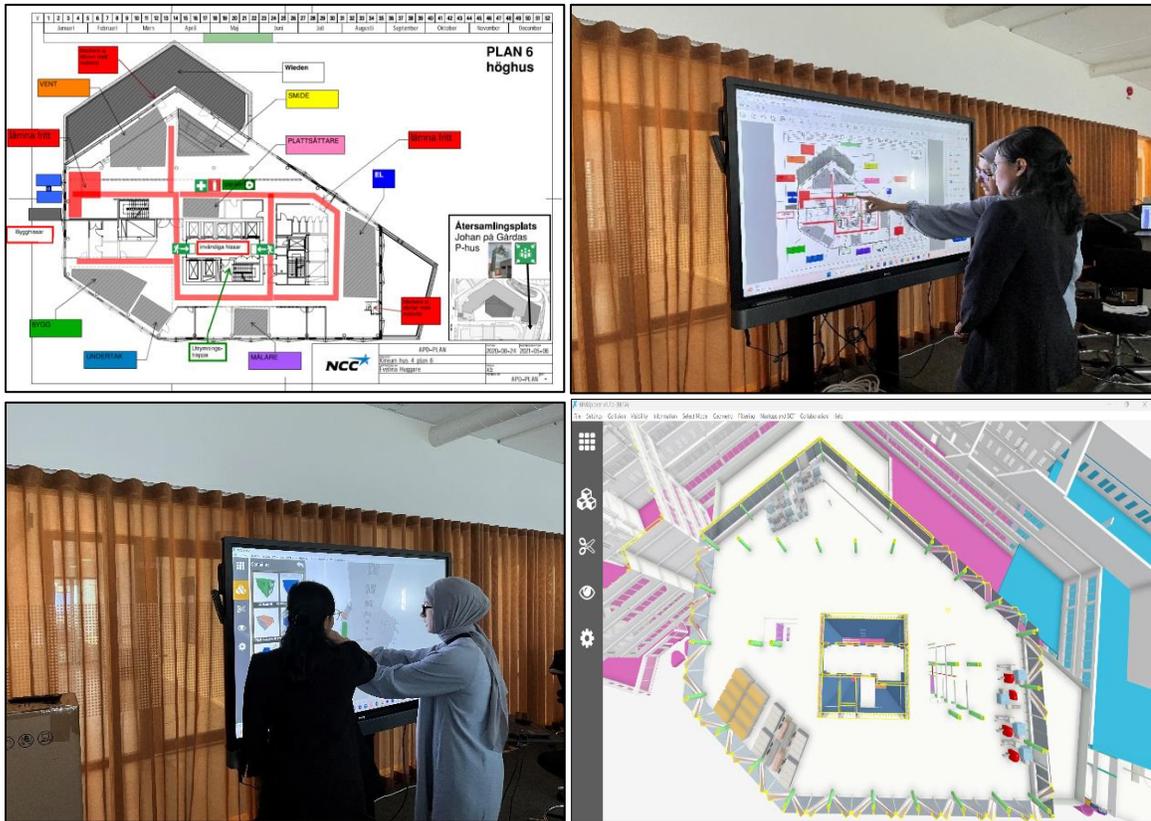


Figure 11. Preparation of site scenario of Kineum floor 6 following the 2D site layout plan of the 6th floor of Kineum Project (May 2021) in BIMXplorer with the help of a touchscreen board.

- **Safe scenario.** The same unsafe scenario with filters was used to plan a safer construction site on the 6th floor of Kineum. As the focus in terms of safety is on openings, safety precautions from different tools for openings are applied to the model. These safety objects were prepared and saved in advance. Loading prefab folders, saving, opening, and adding the prefab files were the main actions in that step as well.

According to the literature review, the concept of prevention through design is highlighted as a means of reducing workplace incidents by incorporating safety measures during the early phase of a project. This subchapter aims to classify possible hazardous situations related to openings on the 6th floor of Kineum and propose mitigation strategies based on the use of PtD toolboxes.

CII Design for Building Safety Toolbox includes five categories that are connected to building openings. As the current case study pertains only to the sixth floor of the Kineum building, a category related to roofing will be excluded from the analysis. On that floor, specific hazardous situations are classified and some resolutions from the safety toolboxes were combined and applied to the project (Figure 12).

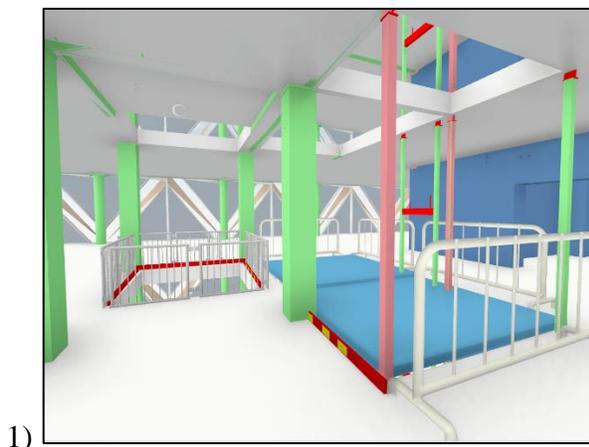
Following the recommendations of the Construction Industry Institute (CII), permanent guardrails were applied around floor openings in concrete slabs, particularly those situated in high-traffic passageways. To prevent tripping hazards, it is advised to keep steps, curbs, and slab depressions away from window openings, exterior edges, and floor openings. In

this case, because the triangular opening connected to a stair and ramp and was located near a window opening, a permanent guardrail was implemented for securing purposes.

The CII toolbox further proposed incorporating warnings in the construction plans and specifications to address design features that give rise to floor openings, such as ventilation systems, trash chutes, and elevators. This suggestion highlights the significance of collaborative efforts and the involvement of design engineers in safety planning. Additionally, it was recommended that the project's permanent guardrail systems be designed and installed early in the construction process to be utilized by all contractors.

In accordance with Sothern Company's Design for Safety Checklist, openings should be located away from passageways and work areas to mitigate fall hazards. Because only permanent openings are examined in this research, this suggestion can offer insights for future project solutions. However, since these openings were located near work areas, precautions, warnings, and permanent guardrails were applied. Unused openings were covered with temporary plywood to prevent material from falling between levels, as welding operations can pose fire hazards due to excessive sparks. This recommendation particularly applied to actively used openings equipped with temporary guardrails, which were unused at the time of the scenario. Another suggestion aligns with the CII suggestion of providing permanent guardrails to prevent falls from heights. Furthermore, toe boards were advised at all slab openings and edges to address the potential risk of workers falling through.

SlideRule primarily focuses on analyzing potential hazards by assessing design choices, solutions, material selection, installations, and other relevant factors. Notably, this tool considers every action a risk for workers, acknowledging that construction sites inherently entail risks, even when safety objects are installed using various methods. Consequently, it is crucial for design professionals to be mindful of this scenario and make informed decisions when selecting design elements and implementing modifications.



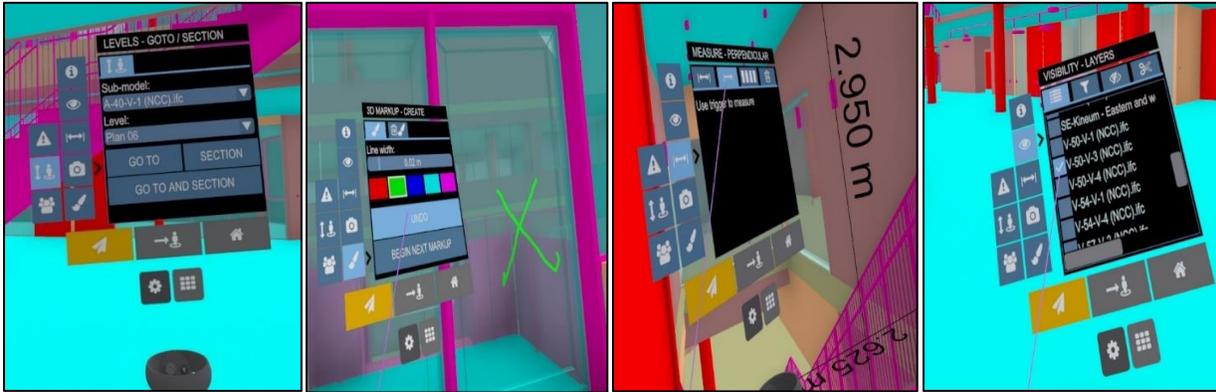


Figure 13. VR features (a) selecting levels and sections; (b) Drawing tool; (c) Measurement tool; (d) Visibility tool to hide/unhide sections.

4.4 Workshop

The topic of the workshop was Collaborative Safety Planning Through Comparison Between 2D and VR. The purpose of the workshop is to discuss how to improve the safety of construction workers by using VR. A virtual walkthrough will be conducted through a multi-user VR setup to investigate if potential hazards can be identified. The aim is to examine if safety planning can be improved during the production planning phase with the help of a VR walkthrough. Also, to investigate if VR can improve collaboration regarding safety planning of construction sites and aid the construction team to be better prepared.

The workshop was conducted at Chalmers, and it lasted for 3 hours. At the beginning of the workshop, a brief introduction of the purpose and background of the thesis, and also the workshop itself were provided. They were followed by an exploration of hazard identification techniques through 2D drawings and virtual reality (VR). The participants will engage in discussions regarding hazardous areas, site layout plan and protective measures for safe sites. The workshop concluded with reflections on the topics covered and an open forum for general questions.

4.4.1 2D Exercise

The participants were provided with printed copies of the 2D plan of floor 6 of the Kineum Project. The participants were then asked to identify some areas in the 2D drawings according to their opinion that can be hazardous during construction period. Since the literature review suggested fall hazards are the most common types of accidents prevalent in the construction industry, this exercise aimed to determine how many potentially hazardous areas, particularly openings, can be identified from a conventional 2D plan view for safety planning. The following questions were provided that guided the participants' what type of hazards they should look for in the 2D drawings. The questions were formulated in such a way that while looking for potentially hazardous areas, participants would especially focus on marking the openings.

- Can you identify any safety issues? Mark potentially hazardous areas according to your opinion.
- Why did you identify this as an issue? Have you had any experience?
- What type of potentially hazardous areas could you identify? What about for openings?
- What can we do to improve the plan in terms of construction safety?
- What kinds of measures can we put to protect the openings? (Guardrails/ Covers)



Figure 14. 2D plan view of level 6 of Kineum Project.

During the exercise, different participants marked and identified different openings as hazardous areas. Except for Researcher 1 and Researcher 3, every participant was already familiar with the 2D plan view prior to the workshop session. All the participants successfully identified and marked the elevator shaft openings and stairwell openings. Among the participants, Researcher 3, and the Lead VDC developer could identify the highest number of openings including elevator shafts, installation shafts, stairwell openings, opening of windows surrounding the façade and the triangular opening near the terrace. However, the other participants did not mark the triangular opening as a potentially hazardous area. According to Design Engineer 1, the connection between the terrace and the floor slab can be dangerous to work with during construction process and he also mentioned that working in the terrace area could be risky as there is a chance of falling objects from the floors above. Furthermore, Design Engineer 1 and Researcher 2 did not identify the opening of windows surrounding the façade as risky areas.



Figure 15. (a) All openings marked in the 2D plan view of floor 6 of Kineum Project; (b) The triangular opening near the terrace that was not recognized by most participants during the exercise.

Other than openings, Researcher 2 also marked some areas that could raise safety issues such as narrow corridor between stairs and terrace area which could be potentially problematic for material handling. Overall, most of the participants pointed out that it is difficult to detect some potentially dangerous areas in a 2D layout since the variation in elevation level cannot be seen from a 2D viewpoint. Regarding planning construction safety and what measures should be taken for protection, only the health and safety engineer and Researcher 1 suggested using permanent guard rails for openings, proper covers for the shafts and temporary structures if needed.

4.4.2 VR Exercise

In the subsequent step of the workshop, further progress was made in the hazard identification process, utilizing the capabilities of VR. To further explore these safety issues, the workshop employed multi-user VR technology to show an unsafe scenario with no safety precautions in place. Participants navigated through the BIM project using multi-user VR and focused on the same safety issues as in the 2D drawing exercise. Participants were instructed to engage in virtual walkthroughs of the 6th floor area of the Kineum project, paying particular attention to the area around the opening, in order to identify potential hazards using VR technology. Subsequently, they were tasked with drawing safety objects in the identified area through a collaborative discussion rather than individually.

To facilitate this exercise, concise instructions were initially provided, outlining the proper utilization of VR equipment. Ensuring that participants were familiar with the process of wearing the VR headsets was emphasized. Additionally, participants were guided on how to navigate seamlessly within the virtual environment, utilizing the hand controller to move forward, backward, left, and right, employing either the thumb stick or trigger button on the controller. Moreover, participants were encouraged to familiarize themselves with the menu options available within the VR interface, enabling them to engage in activities such as marking, drawing on the project, and capturing snapshots, all of which formed the core objectives of this segment of the workshop.

Two users joined and interacted in VR after that the other pair took the turn respectively. While two participants were in the VR, the rest of the participants collaborated at the same time on the project by a touchscreen board (Figure 16). The touchscreen board was integrated into the VR headset to present the ongoing progress of the BIM project, facilitating efficient collaboration and communication.

The following questions were presented to assist the participants during hazard identifications in VR:

- Can you identify any safety issues? Mark potentially hazardous areas during walkthrough.
- Why did you identify this as an issue? Have you had any experience?
- Have you identified any hazardous areas of openings?
- What can we do to improve the project in terms of construction safety?
- What kinds of measures have you put to protect the openings? (Guardrails/ Covers)
- Does VR enable you to see more hazards compared to 2D site planning on PC screen or documents? Do you identify some points during VR walkthrough that you could not see in 2D drawing?



Figure 16. Two participants wearing VR headsets and others joining through the touchscreen board and the projector screen during the VR exercise.

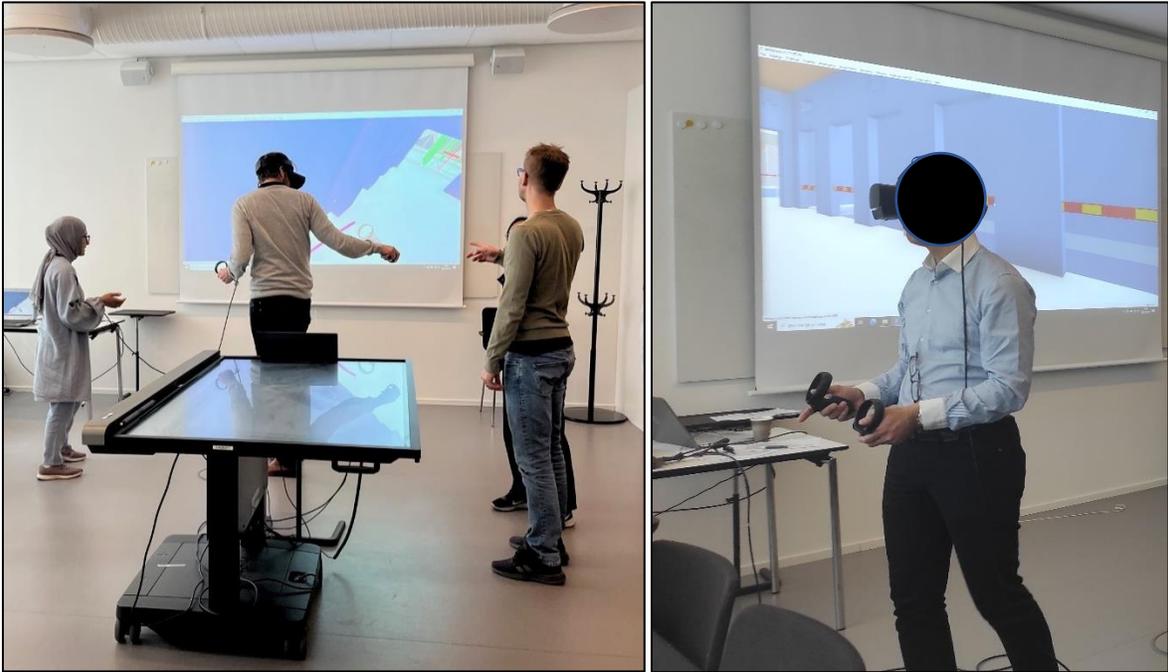


Figure 17. Participants during VR walk through in the simulated BIM model.

The feedback and reflections differed according to the participants' backgrounds and experiences were important to have a productive and efficient outcome for the site planning. Mutli-user walkthrough started with design/structural engineers. For those unfamiliar with VR, the same instructions at the beginning of this exercise were also given when they were in VR.

Each participant successfully completed the VR walkthrough and identified nearly all the openings on the 6th floor of the Kineum project in VR, individually. They utilized the marking tool to sketch guardrails (Figure 18). By leveraging the fly mode functionality within VR, participants can fly to the exact direction and closely examine the details of components and projects. During the utilization of virtual reality (VR) for hazard identification, design engineer 1 examined the column's specifications to verify its accurate installation. Researcher 1, whose background is in

architectural engineering, utilized the fly mode to move outside the building and conduct an in-depth review of the facade's details.

After performing hazard identification in VR, a design engineer realized that the selected case project was a simple example. However, he noted that there could be construction sites with more complex situations. For instance, when buildings are located very close to another building, VR can be even more valuable in offering a comprehensive understanding of hazards and their precautions.

Because these VR activities were done individually, all the participants got together around the touchscreen board where BIM model was opened in BIMXplorer and discussed collaboratively about safe site planning (Figure 19).

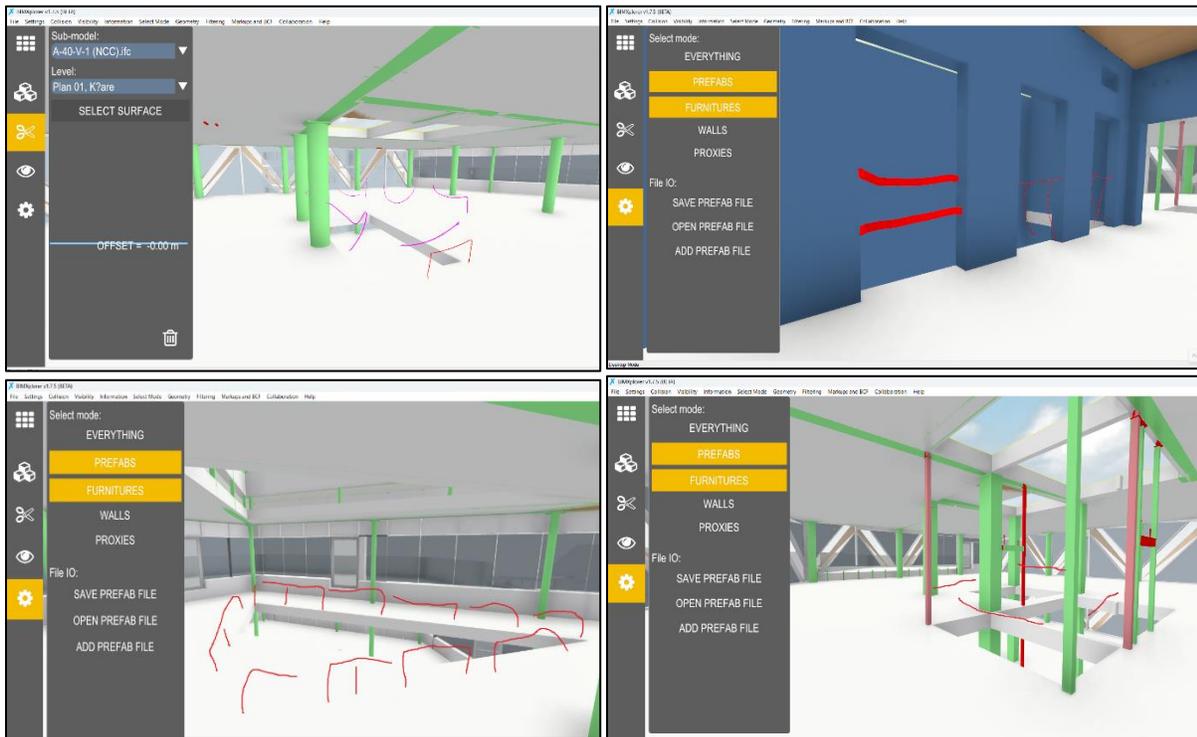


Figure 18. Screenshots of sketched guardrails in several opening by participants in VR.



Figure 19. Participants gathered around the touchscreen board and discussed collaboratively about safe site planning.

Besides the construction solutions of the details of the building, different impacts on construction site safety were also discussed. Researcher 2 described adding sensors, like temperature, humidity, noise, dust, emergency exit, and warning, to measure various conditions of the construction site which could contribute to improving safety. By utilizing virtual reality (VR) technology, these sensors can provide real-time data on several factors that impact safety.

4.4.3 Site layout plan discussion

In this phase of the workshop, to demonstrate if VR could aid in the collaboration between the design team and construction team, a simulated site scenario of the 6th floor of the Kineum project that shows all the subcontractor's areas and their materials in the BIM model according to the 2D site layout plan of the 6th floor of the Kineum Project (May 2021) was presented in the touchscreen board and VR interface. After that, the design engineers and the safety engineer were requested to walk through the VR scenario and discuss site layout plan in VR scenario compared to 2D version. The purpose of this step of VR walkthrough was to look at the site layout plan in a VR interface and compare it with the 2D drawing.

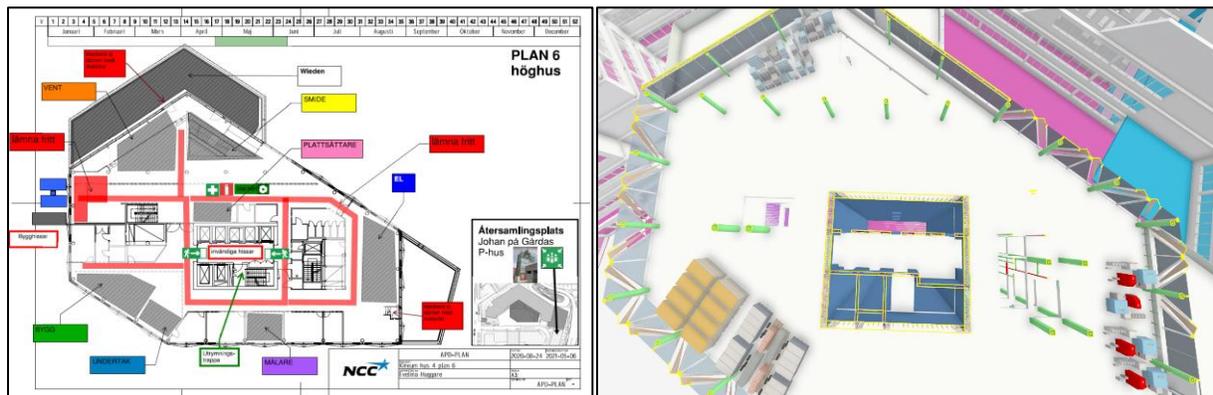


Figure 20. (a) 2D site layout plan of the 6th floor of the Kineum Project (May 2021); (b) simulated site layout plan with subcontractors' materials visible.

During the VR walkthrough, one of the issues raised by the design engineers were that construction workers including subcontractors and safety team often ask design engineers if they can put a certain load (huge pile or stacks of gypsum boards for example) on a particular slab temporarily during the construction process. According to the design engineers, this issue regarding the capacity of slab of taking heavy loads temporarily due to construction process, is usually discussed during the actual construction and not during the planning process. During the discussion the design engineers mentioned that they usually mark the load capacity in a 2D drawing and subcontractors often store the materials according to their experience and not exactly following the marked load capacities. According to both the design engineers, the VR scenario helped them to realize in a better way how narrow or wide the space was compared to the 2D drawings.

After the walkthrough, the design engineers were asked if multiuser VR walkthrough could facilitate collaboration in this regard. In response, the design engineers mentioned since it is possible to navigate the area in 1:1 scale together with the team, it can be beneficial for them to mark the areas more accurately for the load capacities. In addition, they mentioned that because the components, such as stacks of bricks and gypsum boards and other materials, could be seen in

the model, it was possible to determine whether the heavy materials were positioned close or not close to supports or columns. Furthermore, according to the designer engineers and the health and safety engineer, just simply marking some areas in the VR interface that are not permitted for certain loads and providing guidelines regarding it can be beneficial in terms of safety planning. Moreover, it was emphasized that transferring this type of information and knowledge from the design team to construction and safety team through collaboration in VR can also be helpful for both subcontractors and subcontractors' subcontractors for materials storage and arrangements during the construction process. It was further highlighted during the discussion that the information regarding accurate load capacity is even more important for planning infrastructure constructions than building constructions as infrastructure projects involve usage of more heavy machines and vehicles. For effective planning in the design stage, the participants mentioned that the planning process should be started much earlier and there should be accurate simulation for each and every phase of the construction process.



Figure 21. Participants surrounding the touchscreen board during the site layout plan discussion.

4.4.4 Safe scenario presentation through VR

During this step of the workshop, one alternative for a safe site was presented by a multi-user VR, which incorporates suggestions from various tools and regulations that have been implemented on the 6th floor of the Kineum project. The main goal is to provide engineers with a comprehensive understanding of the alternative safe site scenario, demonstrating how and why safety issues were identified and resolved. This presentation serves as a training session aimed at increasing engineers' awareness of safety issues. By increasing their awareness of safety issues and educating them about the practical implementation of safety measures, engineers can be empowered to proactively identify and address potential hazards in their future projects.

During the VR presentation, specific safety concerns were highlighted which were addressed in the alternative safe site scenario. The following questions were asked to assess the participants experience in VR:

- What do you think about identifying the differences of openings and putting safety objects according to different features in VR compared to 2D drawing? Which one would be more efficient in comparison?

- Do you think this immersive experience is beneficial to you to do safety planning in VR than 2D plan or vice versa?
- Do you think structural engineers can apply their knowledge and experience to this process?
- How can we use VR walkthroughs for training of engineers besides of workers?

This multi-user VR presentation encouraged active participation and engagement from the engineers, and provided them with opportunities for discussion, questions, and feedback (Figure 22). During the VR session, the participants realized that the simulated environment they were in, referred to as the "safe site," was safer compared to another unsafe scenario designed for the VR exercise.

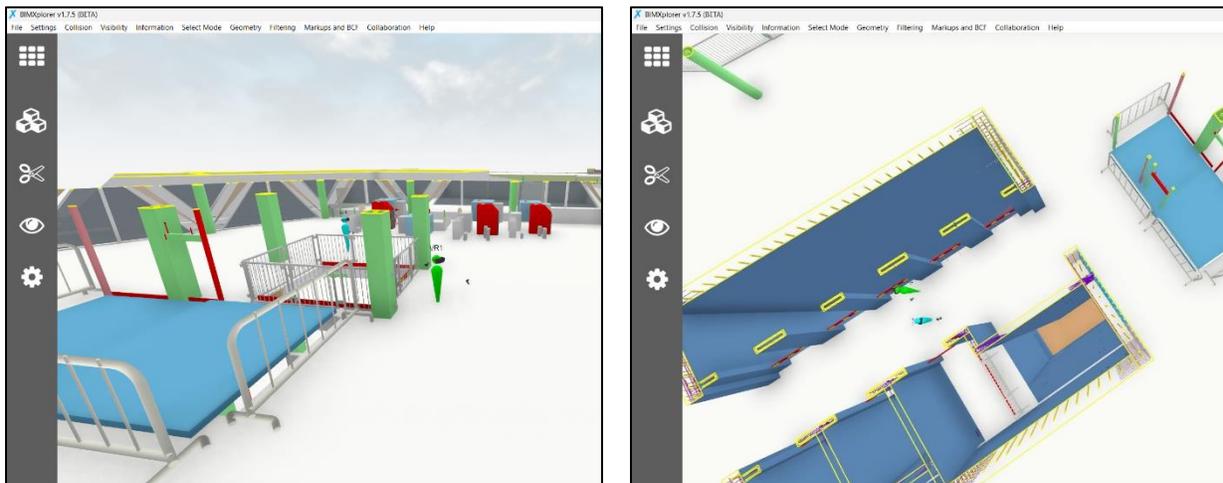


Figure 22. Multi-user VR meeting on discussion about safe site solutions (Different users are visible with different colors of avatars).

During this exercise, participants added extra precautions to the elevator shaft part in the designed safe scenario, where the thesis authors qualified it with light safety precautions (Figure 23). Design engineer 2 also mentioned that they could identify openings in the project and put safety objects that are used commonly, but they are not able to put the right safety objects, and guardrails, according to their features. When it comes to collaboration, the health and safety engineer explained that they are not used to doing any collaborative work for design purposes during the design phase, however, before construction they get together only to discuss site planning. In this regard, he identified a challenge that necessitates collaboration with design engineers: when the decision is made to install guardrails, such as those around the floor perimeter, it becomes important to involve design engineers in determining the appropriate structural solution for their design.

Another point is temporary plywood covering was used in the area where they can be used for lifting materials. An addition to the designed safe site alternative, the health and safety engineer said that they closed the elevator shaft openings with plywood to create platforms for construction workers to work in that area.

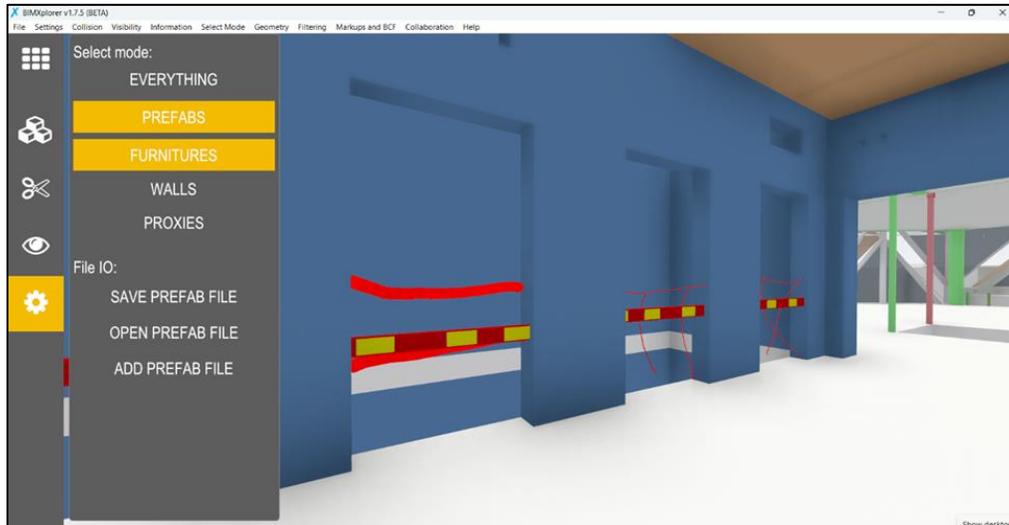


Figure 23. Overlapping view of safety planning in VR with the proposed safe scenario.

4.4.5 Participants' reflections on the workshop sessions

Near the end of the discussions and activities, the participants were asked to answer some questions according to their opinion of the workshop sessions. This final part of the workshop aimed to gather all participants' reflections on the activities with yes/no questions and some optional comments that motivate their answers. In total, there were 19 questions, and the questions were divided into four parts. The first part of the questions involved some general questions regarding participants' previous VR experience and overall impression of using VR during the activity. The second part consisted of questions regarding the user interface and user experience of the VR system. The following part involved questions regarding how multi-user VR facilitates collaboration and decision-making and the final section comprised of questions related to design engineers' attitude and awareness. Although questions regarding the general usability of VR system were asked to the participants in this activity, the purpose of the workshop was not to analyze the usability of the VR environment. The overall aim was to evaluate participants' thoughts on whether VR can benefit safety planning procedures. Table 07 represents the sample reflection questions that were asked to the participants. The responses of all participants are presented in Table 08.

Table 07. Reflection questions for the final session of the workshop.

No	General Questions:				
1	Do you have previous experience of using VR?	Yes	No		
2	If so, in which context or purpose have you used? For work or other purposes such as gaming, commercial marketing?	Training	Simulation	Gaming	Other, write your answer:
3	What was your overall impression of the VR construction site from your activity today?	Write your answer:			
4	Did the VR experience help you understand the layout of the construction site?	Yes	No		
5	Did the VR experience provide a sense of being on a real construction site?	Yes	No		
6	Do you think VR adds value compared to viewing the site plan on a 2D screen? Does 1:1 scale visualization in VR provide better spatial comprehension than 2D drawings and BIM models?	Yes	No		
Regarding usability of VR interface:					
7	Was the interface user-friendly (Was it easy to choose different options)?	Yes	No		
8	Do you feel dizzy or have eyestrain while using the system? Motion sickness?	Yes	No		
9	Do you feel insecure while using the system as you are not aware of what is happening around you?	Yes	No		
Regarding collaboration and decision-making/ participant's viewpoint on VR as a collaborative tool					
10	Do you think VR can be used as a collaboration tool?	Yes	No	Write your answer:	
11	Could you collaborate/communicate and support other participants?	Yes	No	Write your answer	
12	Was multiuser VR helpful in interdisciplinary decision-making?	Yes	No		
13	Do you think collaboration through multi-user VR is better than the conventional methods?	Yes	No	Why? Write your answer (optional):	
14	Do you think VR could facilitate collaboration to improve safety planning and better prepare for safety hazards compared to 2D plan?	Yes	No	Why? Write your answer (optional):	
15	Do you think collaborative VR walkthroughs could be a useful addition for design and safety review for construction projects?	Yes	No	Why? Write your answer (optional):	
Regarding design engineers' awareness:					
16	Do you think structural/design engineers' attitude is important to site safety?	Yes	No		
17	Working besides openings is a risk of fall hazards, do you think design engineers recognize the situation as a safety hazard for workers?	Yes	No		
18	Do you think structural/design engineers are familiar with this type of safety hazard?	Yes	No	Why? Write your answer (optional):	
19	Do structural/design engineers have any influence over such a situation?	Yes	No	Why? Write your answer (optional):	

Table 08. Responses of all participants for reflection questions during the workshop.

Question no.	Design Engineer 1	Design Engineer 2	Health and safety engineer	Lead VDC Developer	Researcher 1	Researcher 2	Reseracher 3
1	No	No	No	Yes	Yes	Yes	Yes
2	-	-	-	Training, Simulation and gaming	Simulation	Training	Research
3	Useful	Good	Interesting, can help us.	Really good	Worked well, navigation challenging.	Has potential.	Good
4	Yes	Yes	Yes	Yes, maybe I am the wrong person since I knew the project from before. But in general, it could be good to see the Room Names in VR (from the spaces).	Yes	Yes	No, the touchscreen board did
5	Yes	Yes	Yes	Yes and no, I think for making it better it could be so that you fall in VR if you walk over an opening or walk outside, So the user experiences the safety hazard.	No	Yes	Yes
6	Yes	Yes	Yes	Yes	Yes, for 2D, VR>2D; no for BIM, VR=BIM.	Yes	Yes
7	No	Yes	Yes	Yes	Yes	Yes	Yes
8	Yes	No	No	No	No	-	Yes
9	No	No	No	No	No	Yes, a little.	No
10	Yes, between designer and site.	Yes	Yes	Yes	Context dependent.	Yes, for details touchscreen board collaboration better.	Yes
11	Yes	Yes	Yes	I didn't test.	No, Communication is difficult.	No	Yes
12	Yes	-	Yes	Yes	-	Yes	Yes
13	Yes, saves time.	Yes and No, VR complements normal 3D, sometimes 2D and 3D is enough or better depends on the project and the tasks.	Yes	Yes	Yes, not better, can help, support but cannot replace.	Partly, a bit excluding with glasses.	Yes, it provides awareness for detailed area.
14	Yes, easier to identify the risk zone.	Yes, Provides better understanding, especially for more inexperienced participants.	Yes	Yes	Yes	Yes	Yes, it helps to convey potential hazards for hard to spot places
15	Yes	Yes	Yes	Yes	Yes	Yes, especially early for temporary work.	Yes
16	Yes	Yes	Yes	Yes	Yes	Yes	Yes
17	Yes	Yes	Yes	Yes	No	Yes, for large openings, smaller environmental problems are trickier.	Yes
18	No, they are not involved in safety discussions yet.	Yes	Yes	-	Yes, Institution.	Yes, for experienced people, but juniors may lack this knowledge.	Yes. The risk is well-known but finding all the occurrences is difficult.
19	Yes	No, we don't design safety rails.	Yes	Yes	No, follow design.	Yes, architects should have this knowledge too.	Yes

5. RESULTS OF THE WORKSHOP

This chapter describes the results of the workshop by analyzing the responses and activities of the participants during the various workshop exercises. Findings from each exercise are documented in separate sections and later they are combined in the discussions chapter to answer the stated research questions.

Results of 2D exercise

From the activities done by the participants during the 2D exercise, it can be said that most of the participants can identify general openings such as the elevator shaft openings and stairwell openings in a 2D plan view drawing. However, some openings that are unique to a project can be challenging to identify only with a 2D drawing. For example, the triangular opening near the terrace was a unique opening in the floor 6 plan which was not recognized by most of the participants during the exercise. Again, according to the participants, identifying hazardous areas from a 2D plan becomes difficult because a 2D viewpoint does not reflect elevation level variation. The findings of this exercise make it clear that only with a 2D plan view drawing, hazardous areas such as openings cannot be identified effectively. As a result, considering and planning safety precautions only based on a 2D layout becomes challenging, just as it is challenging to indicate hazardous areas.

Results of VR exercise

The multi-user walkthrough began with the design and structural engineers (Figure 16, 17). For those who were not familiar with virtual reality (VR), they were given the same instructions both before and during their VR experience. This redundancy led to the realization that instead of providing separate instructions outside of VR, instructions should be provided within the VR environment itself. It can enhance participants' understanding and allow them to receive guidance while fully engaged in the virtual environment.

A comparison between the 2D drawing and VR experiences will likely reveal that VR technology provides a more immersive and realistic experience, allowing users to identify the number and type of floor openings more accurately in a building. Participants identified all the openings that can be risky during the construction, including the triangular one which was not identified during the 2D drawing exercise (Figure 18). They used a marking tool to accurately sketch guardrails. However, they performed the walkthrough individually and the only interaction was discovering each other's avatar in the same virtual model. Due to the individual nature of these VR activities, all participants gathered around a touchscreen board where BIM model was displayed in BIMXplorer (Figure 19). They collaboratively discussed safe site planning using the touchscreen board, which proved to be a more effective collaborative tool. Despite this, VR still provided benefits as it allowed participants to walk through the project and gain an immersive understanding of the site. Design engineer 1 found VR to be a useful tool for hazard identification, particularly in complex scenarios where buildings are close to another building.

During the utilization of virtual reality (VR) for hazard identification, Structural/Design Engineer 1 examined the column's specifications to verify its accurate installation. By using VR, the engineer could visually inspect the column to ensure it was installed correctly. This demonstrates the application of technology in enhancing safety measures in construction.

Furthermore, researcher 1 closely examined the facade's design elements, identified potential hazards, and made informed decisions regarding safety measures. These examples support the notion that safety planning in construction extends beyond simply placing guardrails or safety objects. While physical safeguards are essential, it is equally important to develop appropriate solutions that assist workers in carrying out their tasks safely. The use of VR technology in hazard identification and design review demonstrates how innovative approaches can be employed to minimize risks to workers' safety. The reference to SlideRuLe suggests that every action in construction entails some level of risk to workers' safety. It emphasizes the need for robust design solutions that prioritize construction safety.

Results of site layout plan discussion

From the conversation during the VR walk through for site layout plan discussion, it can be inferred that VR site layout plan can help design engineers in preparing a more efficient site layout plan. While in 2D site layout plan only the areas designated to subcontractors are visible, in the simulated VR site layout plan different materials and components can be viewed in a real scale. By realizing the spatial context in detailed and 1:1 scale, simulated site scenario can support the design engineers in comprehending the purpose of the slab for material storage during construction process. This intuitive understanding of the scale and spatial relationships between different building components and materials can aid in identifying and marking the slab load capacity more accurately than compared to 2D site layout plan.

Together with safety engineers, the VR walk through discussion in the simulated model in the design and planning phase can not only raise awareness of the design engineers regarding safety but also support them in contributing to a better safety plan and strategy. This type of collaboration discussion between design and safety team utilizing the VR can aid in transferring and exchanging knowledge and information between the design and construction phase and can reduce miscommunication. By ensuring better information flow, the construction team would be better prepared and overall safety would be increased.

Results of safe scenario presentation through VR

The proposed alternative safe scenario aimed to be the foundation for new discussions. Several suggestions from the three designs for safety tools were used to simulate that safe scenario. However, an interesting finding emerged from this experiment, indicating that the thesis researchers implemented incorrect safety precautions, despite having access to a list of safety suggestions. The thesis researchers put lighter safety precautions for the elevator shaft section, considering it to be less hazardous than an opening directly facing a traffic way. As a result, the thesis researchers faced the difficult challenge of choosing suitable objects to guarantee optimal safety standards. This issue was also raised during the workshop by a design engineer, who pointed out that while they could identify openings in the project and install commonly used safety objects, they were unable to install the appropriate safety object, such as guardrails, based on their specific features. This outcome highlights the significance of collaboration during the production planning phase and underscores the researchers' limited expertise in safety as architects and engineers.

According to the findings presented in Figure 18, participants utilized marking tools to draw guardrails in a virtual reality (VR) setting, which was perceived as both quick and effortless. This gave the idea for the possibility of conducting future collaborative site planning by allowing design engineers to mark regions for safety elements, such as guardrails, by outlining their boundaries and subsequently incorporating this information into an IFC file. By implementing this practice,

the safety planning process can be enhanced, facilitating the ease of locating appropriate safety objects for the safety design teams based on their expertise. The lead VDC developer also mentioned that this work could have additional benefits in terms of budget calculation for site planning by exporting the data from IFC file.

In this scenario, the temporary plywood coverings were used to close off areas that were not being used temporarily, as well as to prevent welding sparks and objects from falling. The safety engineer also mentioned that during actual construction, these covers were intended to enhance safety by blocking off potentially hazardous areas and providing a stable platform for workers to maneuver on during the construction process.

Results of reflection part

The following section presents the outcomes of participants' reflections on the workshop sessions, which are illustrated in Likert scale diagrams.

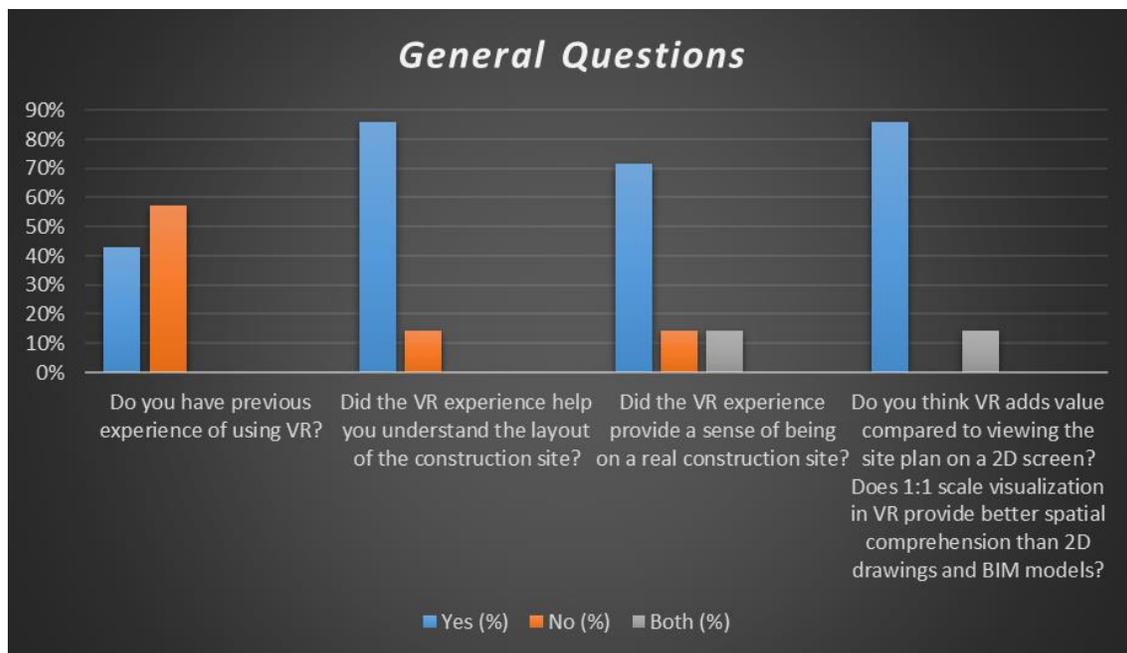


Figure 24. Responses to the general questions.

According to the survey results, 43% of the respondents reported having previous experience with using virtual reality (VR), while the majority (57%) had not. Regarding the effectiveness of VR in understanding the layout of a construction site, 86% of the participants found the VR experience helpful, whereas 14% did not. Similarly, 71% of the respondents felt that the VR experience provided a sense of being on a real construction site, while 14% did not agree and 14% did not share that. The majority (86%) believed that VR adds value compared to viewing site plans on a 2D screen, as the 1:1 scale visualization in VR enables better spatial comprehension compared to traditional 2D drawings and BIM models. Overall, these findings highlight the potential benefits of VR in construction site understanding and spatial visualization.

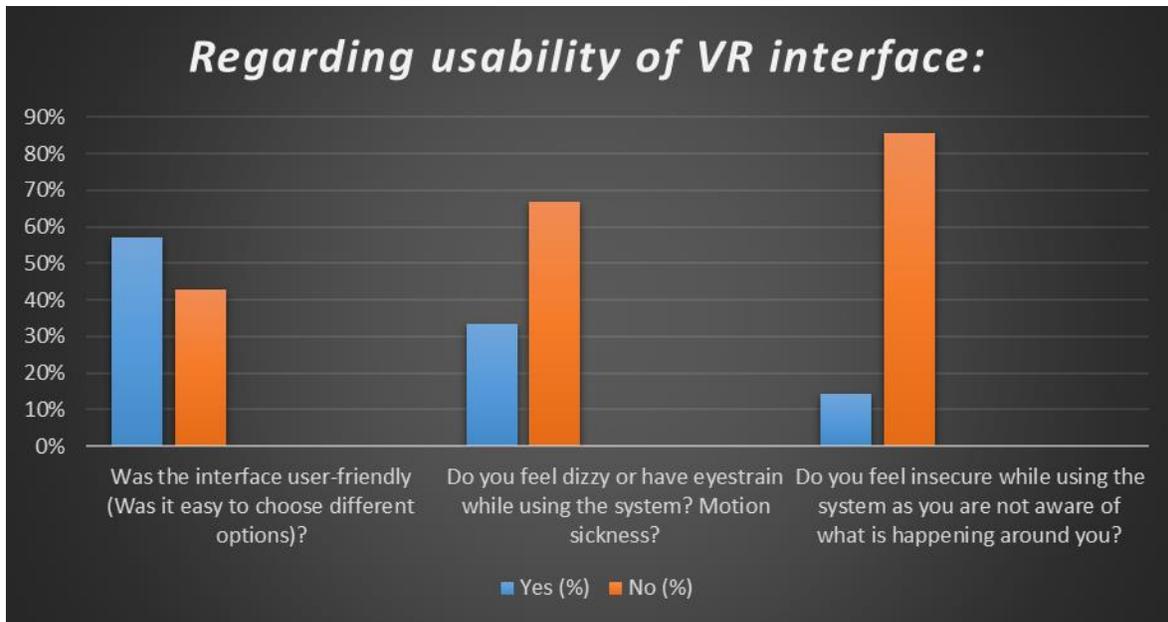


Figure 25. Responses to the questions regarding usability of VR interface.

In assessing the usability of a VR interface, several specific points and differences can be observed from the collected data. Firstly, 57% of the participants found the interface to be user-friendly, indicating that it was relatively easy for them to navigate and select different options. However, 43% of the respondents disagreed on using the interface effectively. Secondly, a minority of 33% reported experiencing dizziness or eyestrain while using the VR system, indicating a potential issue with motion sickness. Conversely, 67% did not encounter such discomfort, highlighting a difference in individual responses. Finally, 14% of participants expressed feeling insecure while using the system, as they were not fully aware of their surroundings. These findings highlight that overall usability of VR interfaces is user-friendly, although some users can face potential issues while using it such as motion sickness, dizziness or eyestrain and insecurity of the surrounding environment.

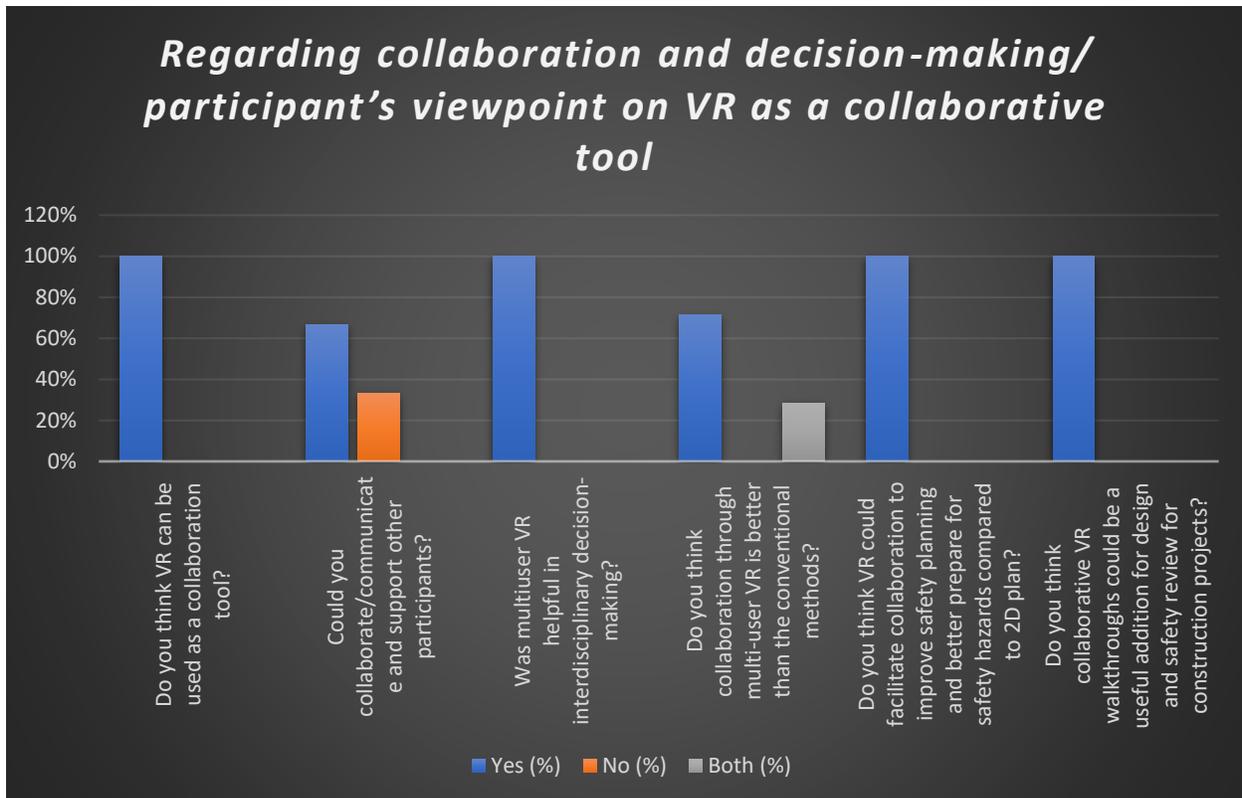


Figure 26. Responses to the questions regarding participant's viewpoint on VR as a collaborative tool.

The findings of this part of the questions highlight some important reflections regarding the use of virtual reality (VR) as a collaboration tool. Firstly, all respondents (100%) agreed that VR can be effectively used for collaboration purposes. However, when asked about their ability to collaborate, communicate, and support other participants in VR, 67% agreed while 33% expressed disagreement. On the other hand, all respondents (100%) acknowledged the benefits of multiuser VR for interdisciplinary decision-making. In terms of comparing VR-based collaboration with conventional methods, 71% of participants believed that VR is superior, while 29% were unsure. Additionally, all respondents (100%) recognized VR's potential for improving safety planning and preparing for hazards, as well as its usefulness in design and safety review for construction projects. In summary, while there was a consensus on the overall value of VR as a collaboration tool and its applications especially in safety planning, there were slight differences in opinions regarding the extent of collaboration in VR.

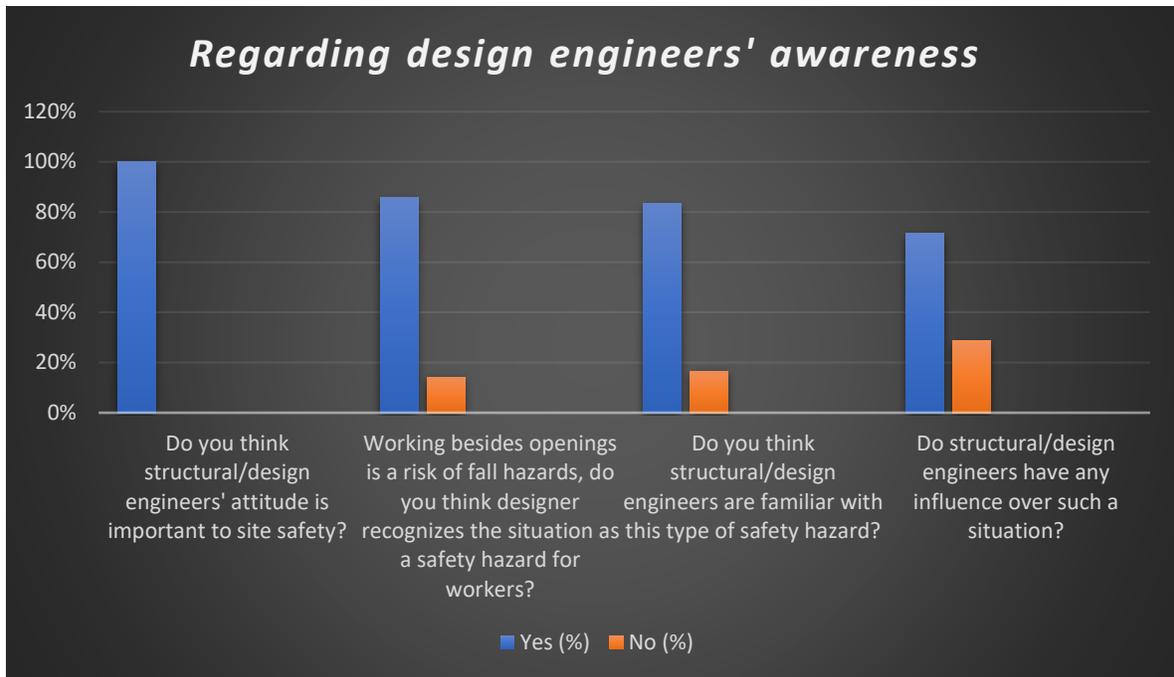


Figure 27. Responses to the questions regarding design engineers' awareness.

The collected data of this part of the questions indicates a consistent agreement among respondents that the attitude of structural/design engineers is crucial for site safety, with 100% recognizing its importance. When it comes to working near openings, 86% of respondents believe that design engineers acknowledge this situation as a safety hazard for workers, while 14% do not share this belief. Furthermore, 83% of participants think that structural/design engineers are familiar with this specific type of safety hazard, indicating a relatively high level of awareness. However, when it comes to their influence over such situations, opinions are slightly divided, with 71% believing that design engineers have an influence, while 29% are skeptical of their impact. These findings highlight the overall recognition of design engineers' awareness regarding site safety, but also indicate room for improvement in terms of influencing and mitigating potential risks.

6. DISCUSSION

This chapter of the study would explore the three stated research questions by evaluating and comparing the findings of the literature review with the empirical study. Moreover, by contrasting and combining relevant findings and arguments, the discussion in this chapter answers the established research questions and presents the key findings and overall outcome of the study.

RQ1. Can VR improve project safety planning in comparison to 2D drawings?

According to Sacks et al. (2015), compared to 2D drawings VR can provide detailed and in depth understanding of hazards, especially for a specific context of a unique project. Supporting this argument, the results of 2D exercise of the workshop indicated that it can be difficult to detect some openings that are exclusive to a project by only using a 2D model. On the other hand, VR exercise during the workshop allowed participants to accurately identify hazardous areas, including unique openings that were not easily recognized in the 2D drawings. While identifying hazardous areas, especially openings, VR appears to require less cognitive effort than 2D drawings and it can provide the actual feeling and sense of falling. This indicates that VR can provide a more comprehensive and realistic representation of the project, enabling stakeholders to identify potential safety risks more accurately. Moreover, virtual walk-throughs can be performed several times to identify a high number of potential hazards.

During the VR exercise, VR walkthrough allowed the participants to conduct visual inspections and in-depth reviews of construction elements. Design engineers were able to visually inspect installations and verify their accuracy, while a researcher conducted a detailed review of the facade's design elements. This showcases how VR can provide a high level of detail and immersion, enabling stakeholders to closely examine potential hazards, conduct detailed inspections and make informed decisions regarding safety measures. In this regard, analysis from the reflection questions provided additional evidence that VR improves spatial visualization and comprehension over conventional 2D drawings.

Again, Wolfartsberger (2019) highlighted the importance of VR's ability to provide the impression of actual dimensions and scales compared to 2D models. Further findings of the literature review suggested that VR by its real scale measurement enables to clearly understand design components such as clashes and a lack of space for installations and maintenance which can facilitate material estimation and logistic planning. Supporting this, findings from VR walk-throughs for site layout plan discussions suggested that design engineers can benefit from a more immersive experience. Unlike 2D drawings where only designated subcontractor areas are visible, simulated VR site layout plans allow for viewing different materials and components in a detailed and real-scale environment. In agreement with this, the analysis of reflection questions also suggested that VR added value in viewing the site plans compared to traditional 2D drawings.

Therefore, the result of our empirical study supports our literature review findings that VR enables to identify possible hazardous areas for a project in the planning phase before the construction process begins (Azhar, 2017) and VR can aid in detecting hazardous areas that are unidentifiable by 2D drawings (Sacks et al., 2015). As such, it can be implied that leveraging VR in construction projects can minimize worker safety risks and promote a more comprehensive approach to safety planning. However, although VR can aid in detecting potential hazards or risky areas, it should be mentioned that identifying hazards by extensive walk-through in complex BIM projects can be a

lengthy and tedious process. Therefore, it is suggested that instead of walking through the whole project for every hazard identification, VR can be used efficiently for detailed review and inspection of specific contexts and cases that involve significant risks or hazards.

It becomes important to highlight whether VR offers a user-friendly interface to learn fast and easily. Regarding this, Ozcan-Deniz (2019) pointed out that the learning curve for VR technology is quick and convenient. This is in line with the analysis result of the reflection question regarding the usability of the VR interface which illustrated that overall VR provides a user-friendly interface. Furthermore, from the responses to the reflection questions, it can be observed that both design engineers did not have any previous experience of using VR before the workshop activity. However, during the VR exercise, with single instructions beforehand, the design engineers could effortlessly utilize the tools and features of VR headsets and controllers in order to detect openings and draw guardrails around it. This demonstrates that VR interfaces can be learned quickly and instantly even without prior knowledge and experience of using it. It is also important to mention some difficulties associated with this technology regarding its usage that were identified during the study. Although tools and features of VR can provide an overall user-friendly interface to identify potential hazards and improve safety planning, analysis of the reflection questions shows that some users faced issues such as motion sickness, dizziness or eyestrain and insecurity of the surrounding environment while using the VR headsets. Users, especially those who suffer a fear of heights or a related phobia, may find it challenging to use.

RQ2. Can VR as a collaborative tool help and facilitate better safety planning?

Responsibility for the health and safety of the construction workers should be collective, including both the design team and the construction team. Therefore, proper collaboration is of utmost importance in terms of producing better safety planning. In this respect, the literature study suggested that one of the most significant advantages of VR is that it improves communication and collaboration (Ozcan-Deniz, 2019). Also, findings from the site layout plan discussion suggested that VR can be a significant collaborative tool for the design and construction team to efficiently discuss and plan issues such as load capacity of the floor slabs for proper material storage. The analysis of the reflection questions further demonstrated that all respondents agreed VR can be an efficient tool for collaboration purpose and decision making in order to enhance safety planning and reviews in construction projects.

This form of collaborative approach indicates the potential for VR to facilitate effective communication and coordination among project stakeholders, leading to more comprehensive safety planning. This suggests that VR can be used to conduct future collaborative site planning, allowing design engineers together with safety engineers to mark regions according to their load capacity, detect areas for safety elements, such as guardrails, and incorporate this information into an IFC file. The simulated safe scenario presented during the workshop, in which safety measures and precautions were taken in accordance with the rules and regulations, can be used as an illustration of how safety planning and proper mitigation strategies can be carried out through VR before the actual construction stage. Implementing this practice, the safety planning process can be enhanced, making it easier to locate appropriate safety objects for the safety design teams based on their expertise. Additionally, during the workshop it was mentioned by the lead VDC developer that this work could have additional benefits in terms of budget calculation for site planning by exporting the data from the IFC file.

An interesting finding of this study was observed following the VR walkthrough for the VR exercise and site layout plan discussion, where participants were able to gather around a touchscreen board to collaboratively discuss safe site planning using the BIM model visible on the board. It was observed during the activities that most of the detailed discussions were performed surrounding the touchscreen board. In this regard, two of the participants responded in the reflection questions that for detailed understanding and collaboration, touchscreen board facilitated better than VR headsets. In the literature review, it is pointed out that single-use VR isolates its user from other group members (Wolfartsberger, 2019) and multi-user VR can facilitate multidisciplinary collaboration and ease communication (Sateei et al., 2022; Podkosova et al., 2022). However, from the empirical study, it was observed that despite the use of multi-user VR, the participants using the headsets were slightly isolated from the rest of the participants and the most engaging discussions took place surrounding the touchscreen board. As such, it can be implied that multiuser VR itself was not sufficient for proper and efficient collaboration. It is important to mention here that during the workshop activities out of the seven participants only two were using VR headsets at the same time, and the headsets were alternately exchanged among the participants. The outcome of the study might differ if all participants wore and used the headsets together at the same time. Thus, for ensuring the most effective use of VR in terms of collaboration and safety planning, from the results of this study, it can be suggested that VR should be used in integration with the touchscreen board until further technological developments are made for the VR system itself.

RQ3. Can VR aid in increasing the awareness of the design engineers regarding safety?

The study conducted by Jin et al. (2019) highlighted the importance of informed decision-making in design and consideration of cumulative risk scores when incorporating safety measures. Although the study does not specifically mention VR, it emphasizes the need for design professionals to be mindful of the inclusion of safety measures and the associated risks in the overall risk assessment process. In this regard, the analysis of the reflection question responses regarding design engineers' awareness indicated that the attitude of design engineers is vital for site safety and design engineers have significant influence in improving safety planning.

Combining the literature review and empirical findings it can be argued that VR has the potential to aid in increasing the awareness of design engineers and planners regarding safety in construction projects. The literature review highlighted the importance of design engineers' role in ensuring safety in the construction industry. However, it was noted that designers often neglect safety considerations until construction process begins, focusing more on the safety of building occupants rather than construction workers (Gambatese & Hinze, 1999; Sacks et al., 2015). Designers may lack knowledge of good safety practices or feel that safety measures are not their responsibility (Brace et al., 2009; Gambatese & Hinze, 1999). On the other hand, the empirical findings demonstrated the potential of VR as a tool for improving site planning and safety design. In the VR exercise, the participants in the study utilized features of VR to mark regions for safety elements, such as guardrails, which was perceived as quick and effortless. This suggests that VR can enable design engineers to actively engage in safety planning by visually identifying and outlining areas that require specific safety objects. This form of approach enhances the expertise of design engineers in safety considerations and facilitates the selection and placement of appropriate safety measures.

Furthermore, according to the empirical results, the use of VR in increasing awareness has shown promising outcomes. The exercise of safe site presentation was conducted as a training session for engineers, specifically targeting safety awareness. This VR presentation employed a multi-user setting, encouraging active participation and engagement from the design engineers. It provided them with immersive experiences within a simulated environment known as the "safe site". Interestingly, the engineers participating in the VR session made a notable observation. By comparing the "safe site" environment with the simulated unsafe scenario, they recognized the stark contrast in safety levels. This realization within the simulated environment served as a powerful tool for increasing their awareness of safety issues. It effectively highlighted the importance of implementing safety measures and showcased the potential consequences of neglecting them. Moreover, during the VR sessions, participants had opportunities for discussion, asking questions, and offering feedback. This interactive nature of the VR experience played a crucial role in the effectiveness of the training. This technology, therefore, holds a tremendous number of potential benefits in this sector. Thus, it can be emphasized that design and construction management education should involve VR training in their curriculum which will contribute to fostering a safety-conscious mindset among the professionals. It is indisputable that design engineers should gain more experience related to construction site process for better safety planning and learning through VR can be a valuable solution for it.

7. CONCLUSION AND FUTURE RESEARCH

Construction sites are inherently dangerous due to the nature of the work involved, and the presence of heavy equipment, tools, and machinery increases the risk of accidents and injuries to a large extent. This study investigates the potential of state-of-the-art technology VR in improving safety planning during the design and planning phase of construction. The method of this study was qualitative with literature review and a workshop as empirical research. Through analysis of the literature and empirical results, the study explores and addresses three identified research questions regarding potential use of VR in improving safety of the construction site.

Based on the findings and discussion, it is evident that VR has the potential to significantly improve safety planning in comparison to traditional 2D drawings. Utilization of VR allows for a more comprehensive and realistic representation of the project, that aids in accurately identifying and visualizing potential safety risks, including unique hazardous areas that may be difficult to detect in 2D drawings. Immersive experience of VR walkthrough with user-friendly interface enables in-depth reviews of construction elements and spatial comprehension of the construction site which ultimately facilitates planning and implementing effective safety measures. However, extensive walk-throughs in complex projects might be time-consuming, thus, VR walkthroughs can be more useful in terms of specific contexts and cases for detailed inspections and reviews. Moreover, VR as a collaborative tool demonstrates its ability to enhance safety planning by improving communication and coordination among project stakeholders. Collaborative VR walkthrough allows for efficient discussions and decision-making regarding safety issues and facilitates the incorporation of safety elements and mitigation strategies into the project design before the construction stage. Furthermore, the use of VR for increasing awareness has a positive impact on design engineers' understanding of safety issues. By leveraging this technology, engineers can be equipped with the knowledge and mindset necessary to proactively identify and address potential hazards, thereby ensuring safer outcomes in their future projects. Despite all these abovementioned advantages, this study's findings recommends that in order to facilitate effective site planning and collaboration, VR could be used in combination with a touchscreen board that also presents the model and scenario together with the VR system. This suggests that the VR system itself requires further progress and advancements. Thus, VR can be characterized as an immature technology that has to be developed further to reach its full potential and benefits.

The contribution of this study lies in the fact that it investigates ways for improving the safety of construction workers. Improving worksite safety and safety precautions should be the highest priority since everyone deserves to come to work in a safe environment and return home safely afterwards. By using real-world professionals to participate in the testing and discussion, the result of this research becomes highly applicable in the context of the industry. By exploring the potential of VR, this study encourages practitioners to invest and implement more into this technology so that maximum benefits can be exploited in terms of safety planning. It should be noted that VR is an emerging technology which is developing and changing at a very fast pace; therefore, it is essential for the practitioners to be up to date with the latest inventions and developments.

Limitations

Since interpretation is subjective by nature and different individuals may arrive at different conclusions or perspectives based on their own experiences and biases, the answers and outcomes of the workshop might be limited by the interpretation's subjectivity. An additional limitation of the study is that the majority of those who participated in the workshop activities were already familiar with the Kineum project and the BIM model, which might have affected the results. Further limitations include other types of hazards or hazardous areas that can occur outside of the construction building such as accidents related to cranes, heavy machinery, heavy vehicles, etc. was not considered. Only fall hazards due to openings in floor plan 6 of the Kineum project were taken into consideration. The chosen floor 6 of the building is being used for an open-plan office which is spacious and less narrow. Some floors above this floor serve as a hotel where the floors are less spacious with more rooms and the construction processes for these floors could be more challenging with the possibility of having more hazardous areas. Technical limitations of this study include difficulties with preparing the different scenarios and transferring them to the VR system.

Future research suggestions

It would be an interesting and valuable addition to the existing studies if future research focuses on the following topics:

- Automatic identification of hazards with the help of AI (Artificial intelligence) for effective implementation of VR technology.
- Modeling real-time construction progress to simulate and integrate in VR.
- As this study only focuses on fall hazards related to openings, more study can be done on how to identify all different types of risks and hazards by involving more real-life case projects.
- The results would be more beneficial if construction workers were included in the research study, thus, future study should be conducted including constructions workers and accordingly safety training can be developed.
- It was identified in the study that using VR headsets can be isolating for the users, thus, further research can be done on alternative VR systems such as CAVE VR.
- This study only focused on implementation of VR in planning phase, future study can focus on a project's whole life cycle including construction, maintenance, and demolition phases in terms of improving safety.
- Again, further research can include identifying and addressing different challenges associated with VR implementation for safety improvement.
- Moreover, future research and implementation efforts can be done to fully realize the potential of VR in terms of enhancing safety awareness among designers and planners.

- Du, J., Shi, Y., Zou, Z., & Zhao, D. (2018). CoVR: Cloud-Based Multiuser Virtual Reality Headset System for Project Communication of Remote Users. *Journal of Construction Engineering and Management*, 144(2). [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001426](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001426)
- Du, J., Zou, Z., Shi, Y., & Zhao, D. (2017). Simultaneous Data Exchange between BIM and VR for Collaborative Decision Making. *ASCE International Workshop on Computing in Civil Engineering 2017*. 1-8. <https://doi.org/10.1061/9780784480830.001>
- DGUV (2020). Statistik Arbeitsunfallgeschehen 2019. *Deutsche Gesetzliche Unfallversicherung*, Retrieved on 8 April 2023 from <https://publikationen.dguv.de/widgets/pdf/download/article/3893>.
- Dharmapalan, V., Gambatese, J. A., Fradella, J., & Vahed, A. M. (2015). Quantification and Assessment of Safety Risk in the Design of Multistory Buildings. *Journal of Construction Engineering and Management*, 141(4), 04014090. [https://doi.org/doi:10.1061/\(ASCE\)CO.1943-7862.0000952](https://doi.org/doi:10.1061/(ASCE)CO.1943-7862.0000952)
- Getuli, V., Capone, P., Bruttini, A., & Isaac, S. (2020). BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach. *Automation in Construction*, 114. <https://doi.org/10.1016/j.autcon.2020.103160>
- Getuli, V., Giusti, T., Capone, P., Sorbi, T., & Bruttini, A. (2018). A Project Framework to Introduce Virtual Reality in Construction Health and Safety. *New Frontiers of Construction Management Workshop*. 9(13). 166-175.
- Guo, H., Yu, Y., & Skitmore, M. (2017). Visualization technology-based construction safety management: A review. *Automation in Construction*, 73, 135-144. <https://doi.org/10.1016/j.autcon.2016.10.004>
- Gambatese, J., & Hinze, J. (1999). Addressing construction worker safety in the design phase: Designing for construction worker safety. *Automation in Construction*, 8(6), 643-649. [https://doi.org/10.1016/S0926-5805\(98\)00109-5](https://doi.org/10.1016/S0926-5805(98)00109-5)
- Gambatese J., N. C. (2015). Construction SliDeRule Case Studies. Oregon State University. Retrieved on 25 March 2023 from <http://www.constructionsliderule.org/case-studies/>
- Gambatese, J. A., Hinze, J. W., & Haas, C. T. (1997). Tool to Design for Construction Worker Safety. *Journal of Architectural Engineering*, 3(1), 32-41. [https://doi.org/doi:10.1061/\(ASCE\)1076-0431\(1997\)3:1\(32\)](https://doi.org/doi:10.1061/(ASCE)1076-0431(1997)3:1(32))
- Hinze, J., & Wiegand, F. (1992). Role of Designers in Construction Worker Safety. *Journal of Construction Engineering and Management*, 118(4), 677-684. [https://doi.org/doi:10.1061/\(ASCE\)0733-9364\(1992\)118:4\(677\)](https://doi.org/doi:10.1061/(ASCE)0733-9364(1992)118:4(677))
- Jin, Z., Gambatese, J., Liu, D., & Dharmapalan, V. (2019). Using 4D BIM to assess construction risks during the design phase. *Engineering, Construction and Architectural Management*, 26(11), 2637-2654. <https://doi.org/10.1108/ECAM-09-2018-0379>
- Johansson, M., & Roupé, M. (2019). BIM and Virtual Reality (VR) at the construction site. *CONVR 2019 Enabling digital technologies to sustain construction growth and efficiency*, 19: 1-10 https://research.chalmers.se/publication/513799/file/513799_Fulltext.pdf
- Johansson, M., & Roupé, M. (2022). VR in Construction – Multi-User and Multi-Purpose. *The 22nd International Conference on Construction Applications of Virtual Reality (CONVR 2022)*. <https://www.researchgate.net/publication/366500786>

- Ku K., (2014). Design Risk Management Practices and Assessment Tools for Safety In Construction: Opportunities for BIM. *Proceedings of the Achieving Sustainable Construction Health and Safety*, 2-3 June 2014, Lund University, Sweden.
- Manu, P., Poghosyan, A., Agyei, G., Mahamadu, A.-M., & Dziekonski, K. (2021). Design for safety in construction in sub-Saharan Africa: a study of architects in Ghana. *International Journal of Construction Management*, 21(4), 382-394. <https://doi.org/10.1080/15623599.2018.1541704>
- Martínez Aires, M. D., Rubio Gámez, M. C., & Gibb, A. (2010). Prevention through design: The effect of European Directives on construction workplace accidents. *Safety Science*, 48(2), 248-258. <https://doi.org/10.1016/j.ssci.2009.09.004>
- McAleenan, C. A. O., David A. O. ICE manual of health and safety in construction. <https://doi.org/10.1680/icemhsc.60104>
- NCC. (2021, April 26). NCC's Kineum project reaches milestone – Platzer assumes ownership next year. Retrieved on 26 April 2023 from <https://www.ncc.com/media/pressrelease/2021/8227de89e73e7207/8227DE89E73E7207/>
- NCC. (n.d.)a. Kineum Gårda, Göteborg. Retrieved on 26 April 2023 from <https://www.ncc.se/vara-projekt/kineum-garda-goteborg/>
- NCC. (n.d.)b. Så här byggde vi Kineum. Retrieved on 26 April 2023 from <https://www.ncc.se/vara-projekt/kineum-garda-goteborg/sa-har-bygger-vi-kineum/>
- OSHA. (2019). Commonly Used Statistics. *OSHA Data & Statistics*. Retrieved on 8 April 2023 from <https://www.osha.gov/oshstats/commonstats.html>
- OSHA. (n.d.). OSHA's Fall Prevention Campaign. *Construction Industry*. Retrieved on 10 April 2023 from <https://www.osha.gov/stop-falls>
- OSHA Training Institute. (2011). *Construction Focus Four Training*. Retrieved on 10 April 2023 from https://www.osha.gov/sites/default/files/falls_ig.pdf
- Ozcan-Deniz, G. (2019). Expanding applications of virtual reality in construction industry: A multiple case study approach. *Journal of Construction Engineering, Management & Innovation*. 2(2). 48-66. <https://doi.org/10.31462/jcemi.2019.02048066>
- Occupational Safety and Health Administration. (2002). Job Hazard Analysis [Brochure]. U.S. Department of Labor. Retrieved from <https://www.osha.gov/sites/default/files/publications/osha3071.pdf>
- Podkosova, I., Reisinger, J., Kaufmann, H., & Kovacic, I. (2022). BIMFlexi-VR: A Virtual Reality Framework for Early-Stage Collaboration in Flexible Industrial Building Design [Original Research]. *Frontiers in Virtual Reality*, 3. <https://doi.org/10.3389/frvir.2022.782169>
- Sacks, R., Whyte, J., Swissa, D., Raviv, G., Zhou, W., & Shapira, A. (2015). Safety by design: dialogues between designers and builders using virtual reality. *Construction Management and Economics*, 33(1), 55-72. <https://doi.org/10.1080/01446193.2015.1029504>
- Sateei, S., Roupé, M., Johansson, M. (2022). Collaborative Design Review Sessions In Virtual Reality: Multi-Scale And Multi-User. *POST-CARBON, Proceedings of the 27th International Conference*

- of the Association for ComputerAided Architectural Design Research in Asia (CAADRRIA) 2022, 1: 29-38 <https://research.chalmers.se/en/publication/530023>
- Shrestha, S., Mishra, A., & Aithal, S. (2022). Assessment of Knowledge & Awareness among the Professionals Regarding the Concept of Safety by Design. *International Journal of Case Studies in Business, IT, and Education*, 93-109. <https://doi.org/10.47992/IJCSBE.2581.6942.0153>
- Speegle, A. (n.d.). The Southern Company's Design for Safety Checklists [XLSX]. Retrieved on 5 May 2023 from <https://designforconstructionsafety.files.wordpress.com/2017/07/prevention-through-design-compiled-items-v-2.xlsx>
- Swedish Work Environment Authority. (2022). Protect yourself from fall hazards (ADI 698), brochure. *Work environment, work, and inspections*. Retrieved on 21 March 2023 from <https://www.av.se/arbetsmiljoarbete-och-inspektioner/publikationer/broschyrer/skydda-dig-mot-fallrisker/>
- Swedish Work Environment Authority. (2022). Building and construction work. *Work environment, work, and inspections*. Retrieved on 24 March 2023 from <https://www.av.se/produktion-industri-och-logistik/bygg/>
- Swedish Work Environment Authority. (2020). Industries at risk. *Work environment, work, and inspections*. Retrieved on 13 April 2023 from <https://www.av.se/arbetsmiljoarbete-och-inspektioner/arbete-med-arbetsmiljon/upphandling-och-arbetsmiljo/riskutsatta-branscher/>
- Swedish Work Environment Authority. (n.d.). Work Environment Act 21 April 2018. Retrieved on 24 March 2023 from <https://www.av.se/sok/?qry=arbetsmilj%C3%B6lagen+kapitel+4>
- Syamimi, A., Gong, Y., & Liew, R. (2020). VR industrial applications—A singapore perspective. *Virtual Reality & Intelligent Hardware*, 2(5), 409-420. <https://doi.org/10.1016/j.vrih.2020.06.001>
- SafetyWorks- Maine Department of Labor (n.d.). Managing Safety and Health. Retrieved on 8 May 2023 from https://www.safetyworksmaine.gov/safe_workplace/safety_management/
- Truong, P., Hölltä-Otto, K., Becerril, P., Turtiainen, R., & Siltanen, S. (2021). Multi-User Virtual Reality for Remote Collaboration in Construction Projects: A Case Study with High-Rise Elevator Machine Room Planning. *Electronics*, 10(22). <https://doi.org/10.3390/electronics10222806>
- U.S. Bureau of Labor Statistics (2021). Fatal occupational injuries for selected events or exposures, 2017-21. *Economic News Release*. Retrieved on 8 April 2023 from <https://www.bls.gov/news.release/cfoi.t02.htm>
- USDDepartmentofLabor. (2011, October 31). *Falls in Construction/Floor Openings* [Video]. YouTube. Retrieved on 20 March 2023 from [Falls in Construction/Floor Openings - Bing video](#)
- Wolfartsberger, J. (2019). Analyzing the potential of Virtual Reality for engineering design review. *Automation in Construction*, 104, 27-37. <https://doi.org/10.1016/j.autcon.2019.03.018>
- Yan, X., Li, T., & Zhou, Y. (2022). Virtual Reality's Influence on Construction Workers' Willingness to Participate in Safety Education and Training in China. *Journal of Management in Engineering*, 38(2). [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0001002](https://doi.org/10.1061/(ASCE)ME.1943-5479.0001002).

Zeng, L., & Li, R. Y. M. (2022). Construction safety and health hazard awareness in Web of Science and Weibo between 1991 and 2021. *Safety Science*, 152, 105790. <https://doi.org/10.1016/j.ssci.2022.105790>

Zhou, W., Whyte, J., & Sacks, R. (2012). Construction safety and digital design: A review. *Automation in Construction*, 22, 102-111. <https://doi.org/10.1016/j.autcon.2011.07.005>

9. STATEMENT OF GROUP MEMBERS CONTRIBUTION

Collaboration statement regarding the thesis work in the master's thesis ACEX30 under the master's program Design and Construction Project Management, Department of Architecture and Civil Engineering, Chalmers University of Technology.

We are confirming that the following group members-

- Aytan Huseynli
- Irina Tasnim

contributed adequately to the development of the thesis report with the title **“Increasing workers’ safety by using Virtual Reality (VR) in the project design and production planning”**.

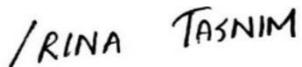
August 28, 2023

Signature 1:



Aytan Huseynli

Signature 2:



Irina Tasnim

10. APPENDIX

Program of the workshop:

- 13:10- 13:15 Introduction of the workshop
- 13:15- 13:35 Hazard identification in 2D Drawing
- 13:35- 14:10 Hazard identification in VR
- 14:10- 14:25 Load-bearing capacity discussions
- 14: 25- 14:40 Safe Scenario presentation
- 14:40- 15:00 Break
- 15:00- 15:15 MEP installation discussions
- 15:15- 16:00 Reflections and general questions