Ebo Kwegyir-Afful

Simulation-Based Countermeasures Towards Accident Prevention

Virtual Reality Utilization in Industrial Processes and Activities

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Tiivistelmä

Vaikka kiinnostus virtuaalitodellisuuden (VR) käyttöön turvallisuuden varotoimissa teollisuudessa on kasvanut, tutkimuksia ei ole juurikaan tehty onnettomuuksien ehkäisystä valmistus- ja kunnossapitotoiminnassa. Tämän väitöskirjan tavoitteena on tutkia ja kokeilla VR:ää tapaturmien ehkäisyssä kohdistuen kolmeen työpaikan turvallisuuden varotoimeen: paloharjoitukset, riskien arvioinnit sekä hätätilanteiden valmiusmenettelyt ja toimintasuunnitelmat (EPR). Kokemuksellisessa ja uppouttavassa koulutuksessa hyödynnettiin kahta teollisuuden 3D-simulointimallia, jotka nojautuvat virtuaalitodellisuuden onnettomuuksien aiheutumismalliin (VR-ACM) (eli 3D-mallinnus- ja simulointi, onnettomuussyy- ja turvallisuuskoulutus) sekä paloharjoitusmalliin. Nämä 3D-simulointimallit ovat litiuminoniakkuja (LIB) valmistava tehdas, joka rakennettiin Visual Components 3D-simulointiohjelmistolla (versio 4.0) ja kaasuvoimala (GPP) Unrealin reaaliaikaisella pelimoottorilla (versio 4.2). Yhteensä viisi tutkimusta (julkaisua) suunniteltiin havainnollistamaan VR:n potentiaalia tapaturmien ehkäisyssä valmistusprosessin layout-suunnittelun ja tehtaan konseptivaiheissa tehtävän kunnossapidon aikana. Kaksi tutkimusta tehtiin LIB-tehdassimulaatiolla vaarojen tunnistamiseksi sekä riskien arvioimiseksi. Tutkimukset tehtiin tehtaan uudelleensuunnittelua varten, työturvallisuuden noudattamisen varmistamiseksi. Muut kolme tutkimusta käsittelevät palovaaran tunnistamista, hätäevakuointia ja riskien vähentämistä huoltotoiminnan aikana GPP-simulaatiossa. Molemmissa tutkimusmalleissa oli useita virtuaalimaailmaan uppoutuneita osallistujia, jotka saivat kokea onnettomuudet yksilöllisesti ja intuitiivisesti. Osallistujat antoivat palautetta kokeen jälkeisessä kyselyssä. Kyselyn tuloksien avulla LIB-tehtaassa tunnistettiin ja lievennettiin useita vaaroja. GPP-kokeilun tulokset viittasivat siihen, että vaikka ylläpitotoiminta virtuaalimaailmassa lisäsi teleläsnäoloa, tilastollisesti merkittävä viive kirjattiin liikettä edeltävässä vaiheessa turvallisuustietoisuuden puutteen vuoksi. Kaiken kaikkiaan tutkimus osoittaa, että VR-laitoksen kunnossapitotoimintaan ja tuotantotehtaan prosessisimulaatioympäristöihin uppoutuvat osallistujat voivat kokea reaaliaikaisia hätäskenaarioita ja olosuhteita, jotka ovat välttämättömiä olennaisten turvallisuustoimien toteuttamiseksi.

Asiasanat: Virtuaalitodellisuus, turvallisuus, varotoimet, onnettomuuksien ehkäisy, 3D-simulaatio.

Abstract

Despite growing industrial interests in fully immersive virtual reality (VR) applications for safety countermeasures, there is scanty research on the subject in the context of accident prevention during manufacturing processes and plant maintenance activities. This dissertation aims to explore and experiment with VR for accident prevention by targeting three workplace safety countermeasures: fire evacuation drills, hazard identification and risk assessments (HIRA), and emergency preparedness and response (EPR) procedures. Drawing on the virtual reality accident causation model (VR-ACM) (i.e., 3D modelling and simulation, accident causation, and safety drills) and the fire evacuation training model, two industrial 3D simulation models were utilized for the immersive assessment and training. These were a lithium-ion battery (LIB) manufacturing factory and a gas power plant (GPP). In total, five studies (publications) were designed to demonstrate the potential of VR in accident prevention during the manufacturing processes and maintenance activities at the facility conceptual stages. Two studies were with the LIB factory simulation to identify inherent hazards and assess risks for redesigning the factory to ensure workplace safety compliance. The other three studies constituted fire hazard identifications, emergency evacuations and hazard control/mitigations during the maintenance activity in the GPP simulation. Both study models incorporated several participants individually immersed in the virtual realm to experience the accident phenomena intuitively. These participants provided feedback for assessing the research objectives. Results of the studies indicated that several inherent hazards in the LIB factory were identified and controlled/mitigated. Secondly, the GPP experiment results suggested that although the maintenance activity in the virtual realm increased the perception of presence, a statistically significant delay was recorded at the pre-movement stage due to the lack of situational safety awareness. Overall, the study demonstrates that participants immersed in a VR plant maintenance activity and manufacturing factory process simulation environments can experience real-time emergency scenarios and conditions necessary for implementing the essential safety countermeasures to prevent accidents.

Keywords: Virtual reality, safety countermeasures, accident prevention, 3D simulation.

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All glory, praise, and honour to "my Lord and my God!" Jesus Christ [John 20:28].

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Contents

Figures

Tables

Abbreviations

3D	three dimensional
4D CAD	4-Dimensional computer-aided design
AAWS	automotive assembly worksheet
ACM	accident causation model
ASET	available safe egress time
CAD	computer aided design
CAVE	cave automatic virtual environment
CREAM	cognitive reliability and error analysis methods
DGBL	digital game-based learning
DHM	digital human models
EPR	emergency preparedness and response
ELT	experiential learning theory
FED	fire evacuation drills
FIOH	Finnish Institute of Occupational Health
FTA	fault tree analysis
GPP	gas power plant
H–R	human-robot
HAZOP	hazard and operability
HFACS	human factor analysis and classification system
HIRA	hazard identification and risk assessment
HMI	human-machine interface
HRWC	human-robot work collaboration
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JSHIRA	job safety hazard identification and risk assessment

LIB	lithium-ion battery
Ltravel	traveling time
MCS	Monte Carlo simulation
MORT	management oversight and risk tree
MSD	musculoskeletal disorder
OHSMS	occupational health and safety management system
omVR	oil refinery VR
RO	research objectives
RQ	research questions
RSET	required safe egress time
PEEP	personal emergency evacuation plan
PTSD	post-traumatic stress disorder
SA	situational awareness
SAVE	safety analysis with virtual environments
SHE	Safety, health and environment
SLIVeR	safety learning in immersive virtual reality
SSQ	simulator sickness questionnaire
STEP	sequential timed events plotting
SQ	sub question
SUSQ	Slater–Usoh–Steed questionnaire
Tdet	detection time
Tpm	pre-movement time
Ttravel	traveling time
TENK	Finnish National Board on Research Integrity
VE	virtual environments
VRE	Virtual reality environment

VR-ACM	virtual reality-based accident causation model
VR	virtual reality
VRISE	VR-induced symptoms and effects
VRML	virtual reality modelling language
VR-PtD	virtual reality prevention through design
VR-SG	virtual reality-based serious games
VRTS	virtual reality training system
WSA	work safety analysis
WS	Witmer-Singer
WSC	workplace safety checklists

Publications

This dissertation constitutes five publications, referred to in the text as

1. **Kwegyir-Afful E**., Lindholm M., Tilabi S., Tajudeen S., Kantola J. (2020) Optimising Occupational Safety Through 3-D Simulation and Immersive Virtual Reality. In: Cassenti D. (eds). AHFE 2019. Advances in Intelligent Systems and Computing, vol 958. Springer, Cham. https://doi.org/10.1007/978-3-030-20148-7_10

2. **Kwegyir-Afful, E**., Kantola J. (2021) Simulation-Based Safety Training for Plant Maintenance in Virtual Reality. In: Cassenti D., Scataglini S., Rajulu S., Wright J. (eds) Advances in Simulation and Digital Human Modeling. AHFE 2020. Advances in Intelligent Systems and Computing, vol 1206. Springer, Cham. pp 167-173. https://doi.org/10.1007/978-3-030-51064-0_22

3. **Kwegyir-Afful, E**., Tajudeen Ola Hassan & Jussi I. Kantola (2021) Simulation-based assessments of fire emergency preparedness and response in virtual reality, International Journal of Occupational Safety and Ergonomics, 28:2, 1316-1330, https://doi.org/10.1080/10803548.2021.1891395

4. **Kwegyir-Afful, E**. (2022). Effects of an engaging maintenance task on fire evacuation delays and presence in virtual reality. International Journal of Disaster Risk Reduction,102681. https://doi.org/10.1016/j.ijdrr.2021.102681

5. **Kwegyir-Afful E**., Toshev R., Helo P., Kantola J., Factory Layout Design and Optimization Focusing on Accident Prevention. (*Under review*)

The author's contributions to the above publications

- Publication 1: The author of this dissertation, herein referred to as the author, is both the lead author and corresponding author who designed the study, modelled the factory, and built the 3D LIB manufacturing simulation with the fourth co-author. In addition, the experiments with the participants were conducted with the third co-author. Also, the second and third co-authors contributed to writing the article, while the fifth author provided valuable comments and supervised the study.

- Publication 2: The author is the lead author and the corresponding author who designed the study, organized the experiments, and wrote the article. However, the second author commented on the paper's structure and contributed to the discussions and methods of the study.

- Publication 3: The author, as the corresponding author, designed the study, conducted the experiments, and wrote the article while the second co-author analyzed the data. The last co-author contributed to the discussions and suggestions for improving the writing.

- Publication 4: As the lead author, this study was exclusively the work of the author, who was the corresponding author.

- Publication 5: The lead author conducted the experiments with guidance from the second author, while the other authors provided imputs for improving the article.

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- Publication 4 is also reprinted with the kind permission of the Elsevier publishing company.
- Publication 5 is currently under review.

Other publications produced by the author during the PhD process

I. Daneshpour, H., & **Kwegyir-Afful**, E. (2021). Analyzing Transdisciplinary Education: A Scoping Review. Science & Education, 1-28. https://doi.org/10.1007/s11191-021-00277-0

II. **Kwegyir-Afful, E.**, Lotchi, K., & Zafar, A. (2019). An axiomatic design approach towards optimizing collaboration amongst SMEs. In M. Merivirta, Pienikin iskussa. Näkemyksiä mikro- ja pk-yritysten työhyvinvoinnin kehittämiseen työn muotoilun keinoin (pp. 71-85). Rovaniemi: Lapin ammattikorkeakoulu. ISBN 978-952-316-331-7

III. **Kwegyir-Afful, E.**, Kwegyir-Afful, E., Addo Tenkorang, R., & Kantola, J. (2017). Effects of Occupational Health and Safety Assessment Series (OHSAS) Standard: A Study on Core Competencies Building and Organizational Learning. In J.I. Kantola et al. (eds.), Advances in Human

Factors, Business Management and Leadership AHFE2017 (Vol. 594, pp. 395-405). Cham, Switzerland: Springer International Publishing AG 2018. doi:10.1007/978-3-319-60372-8_1. https://link.springer.com/chapter/10.1007/978-3-319-60372-8_3

IV. Lotchi, K., **Kwegyir-Afful, E**., & Zafar, A. (2019). Pisku inter-firm E-collaboration platform for SMEs. In M. Merivirta, Pienikin Iskussa. Näkemyksiä mikro- ja pk-yritysten työhyvinvoinnin kehittämiseen työn muotoilun keinoin (pp. 87-95). Rovaniemi: Lapin ammattikorkeakoulu. ISBN 978-952-316-331-7

V. Lotchi K., **Kwegyir-Afful E**., Zafar A., Sivula A., Kantola J. (2020) Intermediary Organization and Collaboration Platform for SMEs. In: Kantola J., Nazir S. (eds) Advances in Human Factors, Business Management and Leadership. AHFE 2019. Advances in Intelligent Systems and Computing, vol 961. Springer, Cham. doi.org/10.1007/978-3-030-20154-8_11

VI. Zabolotnyy, S., Timilsina, B., Daneshpour, H., & **Kwegyir-Afful, E**. (2016). Balancing Conventional Dimensions of Competitive Priority and Sustainability Dimensions: A Perspective to Value-Based Management. In A. O. UNIVERSITY, MODERN ECONOMY (GOSBODARKA WSPOLCZESNA) (pp. 93-109). Warsaw: Warsaw University of Life Sciences.

VII. Zafar, A., **Kwegyir-Afful, E.,** & Lotchi, K. (2019). The complexity and fragmentation of work - Towards a collaborative platform. In M. Merivirta, Pienikin iskussa. Näkemyksiä mikro- ja pk-yritysten työhyvinvoinnin kehittämiseen työn muotoilun keinoin (pp. 25-29). Rovaniemi: Lapin ammattikorkeakoulu. ISBN 978-952-316-331-7

VIII. Zafar, A & Kantola, J, Sivula A., Lotchi K., **Kwegyir-Afful E**., 2019, 'Finnish SMEs and the development of the innovative collaboration platform', ISPIM Innovation Conference Celebrating Innovation - 500 Years Since Da Vinci 16-19 June 2019 At Florence, Italy. The publication is available https://ispim.site-ym.com.

1 INTRODUCTION

According to the global estimates of occupational accidents and illnesses, there are 2.78 million work-related fatalities annually (Takala et al., 2017). Besides the financial implications of high insurance premiums and legal fines, the burden on families and losing loved ones cannot be quantified in monetary terms. For this reason, the International Organization for Standardization (ISO) requirement for occupational health and safety management system (OHSMS) emphasizes instituting proactive safety measures to address these preventable losses (ISO 45001: 2018). Furthermore, research indicates that adherence to active and robust occupational safety practices ensures adequate emergency preparedness, significantly increasing safety awareness and reducing industrial accident rates (Bhide, 2017; Eiter & Bellanca, 2020). Moreover, the absence of relevant hazard identification and risk assessment (HIRA) procedures coupled with the lack of proper safety training as well as inadequate emergency preparedness and response (EPR) programs contributes to increasing accidents and unwanted industrial occurrences (Kjellen & Albrechtsen, 2017). However, traditional methods such as lectures, videos, or PowerPoint have been minimally effective in applying these safety countermeasures in high-risk occupational environments. For example, Lovreglio et al. (2021) compared the effectiveness of VR-based fire extinguishing training to video training and established that the VR participants acquired better knowledge than the latter.

Similarly, Dado et al. (2018) suggest in VR for hazard identification that the technology offers a viable alternative to a natural environment. Besides, exposing humans to real hazardous emergencies is unethical and methodologically inappropriate to observe reactions to real-life threatening conditions (Akdere et al., 2021). According to several empirical findings (e.g., Din & Gibson Jr, 2019; Y. Feng et al., 2022; Liu et al., 2021), such settings are monotonous and lack interactions for experiential learning. Due to these limitations of traditional methods, which predominantly refer to classroom-based settings, and the increasing role fully immersive VR simulations plays in safety, the technology is growing and gaining popularity in some industrial fields, leading to several VR safety improvement modules for hands-on job-related industrial exposure. This span across, for example, a 720-degree flight simulator model for training in aviation safety (Chittaro et al., 2018). VR-based building information models (BIM) for fall prevention in construction (Getuli et al., 2020). VR mine safety training system for training miners in real-life blasting scenarios (Dhalmahapatra et al., 2021; H. Zhang et al., 2019) virtual reality accident causation model (VR-ACM), which was initially designed for accident investigations but is currently used mainly for safety training, and (Din & Gibson Jr, 2019) virtual reality-based accident prevention through design (VR-PtD) concept. VR has thus been utilised effectively for promoting occupational safety countermeasures predominantly in high-risk occupational settings, as explained above(Dhalmahapatra et al., 2020; Karkoszka, 2020). However, other high-risk occupational exposures such as manufacturing and gas-fired power industries are only at the threshold of adopting VR for human safety. Besides, the few studies that address this concern are scattered and lack relevant activity-based simulations, which are necessary for interactivity as a measure of the sense of presence and hands-on training exposure. Therefore, this study focuses on unearthing the factors that explain the uses of VR in safety countermeasures comprising safety training, HIRA, and EPR. Specifically, the study examines how these apply in a high-risk plant simulation activity and a manufacturing factory process simulation.

In addressing this objective, the study first assesses the proximity and suitability of 3D simulations in VR for safety training in emergency fire evacuations and EPR in a plant simulation. Secondly, the possibility of identifying workplace hazards and risks for conducting a HIRA procedure in a VR manufacturing simulation facility. Thirdly, the study performs emergency fire evacuations that subject participants to specific activities to understand the technology's suitability in situational safety awareness, pre-evacuation delay assessments, and evacuation preparedness.

1.1 Background of the research

Although VR was initially designed for games, process designs, and product-oriented technologies, applications for human factors are currently increasing. In the military, VR has been applied as a combat-related post-traumatic stress disorder (PTSD) therapy. Example Virtual-Iraq was used to treat returning soldiers diagnosed with anxiety disorders (Jaffee, 2016). Immersive simulations enable the training of workers in hazardous situations by creating the environment for the necessary reactions rather than watching and listening as experienced in video lessons. For this reason, giants in the oil and gas industry like ExxonMobil and British Petroleum (BP) utilise simulation-based training (SBT) exercises for emergency exit procedures to enable workers to attain safety know-how during emergencies and gain acceptance for safety competencies. Bilotta et al. (2013) report that the advantages of SBT exceed apprenticeship in terms of information absorption, memory retention, learning speed and practical capabilities in any specific safety countermeasure (Bilotta et al., 2013). The medical field has also achieved impressive strides utilising VR to expose trainee medical professionals to high-risk and complicated procedures before delicate surgeries(Lawson et al., 2016; Shaw et al., 2019). Besides, in treating anxiety disorders, VR is exploited by exposing patients to a virtual environment related to fear (Freitas et al., 2021). Likewise, training improves patient safety and emergency medical response (Freitas et al., 2021; Torda, 2020).

VR is employed to prevent accidents and fatalities during pilot training in aviation. A typical example is the flight simulator (Chittaro et al., 2018; Lawson et al., 2016). Results from empirical research indicate that VR is suitable for flight passenger safety training. Secondly, participants also performed faster with fewer errors than those who used PowerPoint and other conventional methods. Thus, with VR, trainees received appreciable and insightful levels of safety self-efficacy (Chittaro et al., 2018). VR is likewise employed to boost safety in the construction industry (Aven & Flage, 2017) and for fire safety training (Schröder et al., 2020), as well as in naval safety (Sermet & Demir, 2022). VR is an effective tool for road safety in educating drivers on safe driving during normal conditions and emergencies (Zhou et al., 2022). The technology has succeeded in disaster preparation by maintaining high memory retention as a viable tool for disaster preparedness (Chittaro et al., 2018).

In another study about safety at the mines, participants indicated that the VR experience replicates extreme incidence scenarios (H. Zhang et al., 2019). Wolf et al. (2022) also reported that VR offers the best method for identifying hazards and analysing risks for accident reconstructions and scenarios needed in safety training (Wolf et al., 2022). The application of high-quality 3-D graphics with sound based on dynamic simulation in the VR ACM provides engaging and exciting experiences for education and training necessary for industrial accident preventive measures (Dhalmahapatra et al., 2021).

1.2 Traditional Safety Practices and VR

Traditional safety practices refer to the status quo of safety practices usually employed for static human error analysis and hazard recognition. Hermann et al. (2010) explain static traditional safety practices as on-the-job exposure and off-site training in classroom practices like lectures, PowerPoint presentations and safety videos. Although several benefits have been cited in the literature regarding traditional safety methods, recent socio-technical industrial working environments require active safety countermeasures to address the industrial interrelationship and interactions between human, technology and organizational aspects (Dhalmahapatra et al., 2020. These benefits include improved safety compliance, cost-effectiveness with enhanced worker interactions, and extensive knowledge impartation etc. (Bensilum & Purser, 2003). Besides, researchers (e.g., Lovreglio et al., 2021; Morélot et al., 2021; Nazir & Manca, 2015) have cited inefficiencies, low retention, and lack of engagement to the accident phenomenon, among other deterrents for traditional safety practices. VR simulations with seemingly hazardous scenarios, conditions, and effects, on the other hand, have proven more effective for safety countermeasures (Chittaro et al., 2018). Din et al. (2019) experimented with virtual reality serious games (VR-SG) for prevention through design (PtD) while assessing the technology's pedagogical value with subjects in construction and maintenance activities. They found it to be more effective when compared to ordinary lectures. Leder et al.'s (2019) study that compared VR with PowerPoint found no statistical evidence to suggest the superiority of VR for enhancing safety training and emergency response (Leder et al., 2019). However, Leder et al.'s (2019) research was seriously limited since their simulation was non-immersive and did not also involve interactions with virtual objects. Therefore, the participants in the study only observed events in three dimensions. Besides, several studies, such as Lovreglio et al. (2021) and Dhalmahapatra et al. (2020), indicate that traditional safety videos and manuals are inadequate when preparing for crisis and that VR has several benefits for safety improvement (Dhalmahapatra et al., 2020; Lovreglio et al., 2021). Some of these benefits are.

- VR provides real-world scenarios, objects, and real-time experiences such as factory processes for human reactions needed in experiential learning for measuring user behaviour (Cano Porras et al., 2018).
- VR improves retention when employed in handling hazardous situations, which is necessary for safety training (Berg & Vance, 2017).
- Safety countermeasures can be conducted remotely and miles away from the factory/plant premises(Kinateder et al., 2014).

- VR can generate a complete artificial 3D perception of a real-life situation (Aromaa & Väänänen, 2016). Likewise, detailed videos were considered alarming in some instances, and only about half of the safety information could be recalled in Aromaa and Väänänen's study. Interactive simulations in VR can thus buttress passive forms of safety interventions (Wolf et al., 2022). For this reason, several technologies have been fused into VR for optimal performance for improved safety.
- Safety training in VR is flexible and can be gamified to make learning more engaging and exciting to promote outstanding cognitive benefits (Radianti et al., 2020).

- VR safety interactions can positively impact an organisation's safety culture by allowing the entire workforce to participate in a unified VR simulation to create a safety-conscious environment (Zhao & Lucas, 2015).

Despite these benefits, some limitations have also been cited in the literature regarding the implementation of VR for safety countermeasures, such as:

- Immersive VR simulations require specific software that can only be run on computers with high processing power and compelling graphic cards to visualise the multi-faceted simulation phenomena. For this reason, most standard computers are unsuitable for running VR applications.

- Besides, there are currently three types of HMD devices (i.e., Head Mounted Display Standalone (HMD-SA), HMD with tracing system, HMD with Corner Cave System (CCS). While testing the effectiveness of each design, Alhalabi (2016) discovered that each type of VR device offered different results in terms of the level of reality, speed of movement and, therefore, participants' telepresence experience.

- Although the prices of state-of-the-art VR gadgets have gradually reduced in recent years, affordability issues still exist for less privileged people and situations. Thus, cost implications for traditional safety countermeasures are relatively lower compared to technology-based training methods.

- Several research findings, e.g., Dado et al. (2018) and Martirosov et al. (2022), have also sighted issues of cyber sicknesses such as nausea, headache, and dizziness with crashing onto objects as associated with fully immersive VR environments. Thus, raising safety concerns about the technology being employed for safety countermeasures.

Meanwhile, traditional safety countermeasures do not experience these issues. For these reasons, although this dissertation emphasizes accident prevention through VR intervention, it also embraced formal aspects during the experiment. For example, participants' pre-experiment instructions were given in the traditional paper and pen classroom format. Likewise, the data collection process from participants after the experiment.

1.3 VR Technologies and Models for Safety

VR technologies and models for safety include the internet-based virtual reality facility layout system (IVLS) and the virtual reality modelling language (VRML).

Applications of these models involve implementing simulation-based algorithms into the human-machine interface (HMI) (Afzal & Shafiq, 2021; Or et al., 2009). Equally, the safety enhancements cave automatic virtual environment (CAVE) based simulations have been assimilated into the VR environment to assess employee safety while operating machinery (Bhide, 2017; Nedel et al., 2016; Yuen et al., 2010). On the other hand, digital human models (DHM) are used within ergonomic risk assessment simulations together with the automotive assembly worksheet (AAWS) to enhance safety while working with and around robots (Oyekan et al., 2019). Other works include realistic DHM representations through comprehensive risk assessment models for providing a holistic and detailed perception of human factors to assist in compiling databases for movements and posture interfaces (Norazahar et al., 2018). Additionally, both Nedel and Bhide employed the virtual reality training system (VRTS) for human-robot (H–R) collaborative training (Bhide et al., 2015; Nedel et al., 2016). Furthermore, Määttä (2007) established that 58% of all machine work-related hazards in a steel factory could be identified through 3-D virtual environments (VE). Thus, these models attest to the various technologies in VR available for applications in industrial safety countermeasures.

1.4 Industrial Applications

Occupational safety regulations reinforce training and risk assessments that are vital in improving safety (Takala et al., 2017; Wolf et al., 2022). In a review by Choi et al., the authors reported that even though most companies in manufacturing employ VR for activity-related training, most of these do not apply the technology to promoting human factors (Choi et al., 2015). For instance, in their report, only four of the 154 articles reviewed between 1992 and 2014 regarding VR utilisation in manufacturing addressed the human element. Two touched on safety training (Qiu et al., 2013), another on human-robot collaborations (Or et al., 2009), and the other on assessments of a safe working environment for the disabled (Budziszewski et al., 2016). Meanwhile, there is a growing concern for rigorous risk assessments and authentic safety training to mitigate accidents and injuries in this sector (Aven & Flage, 2017; Dado et al., 2018). Other industrial applications of VR for safety include human-robot collaborations and human-machine interactions. Some VR experimental studies take steps to minimise symptoms of simulator sickness by incorporating the simulator sickness questionnaire into their experiments (e.g., Rzeźniczek et al., 2020). A comprehensive list of safety criteria was also reported for the facility layout designing phase towards improving health and safety environment (HSE) regulations by Moatari-Kazerouni et al. (2015). The list includes safety during services and maintenance, the security of equipment and machinery, safety in handling materials, environmental aspects, risk hazard assessment and safety training.

1.5 Imminent works

Impending VR projections include considerations for programming an activity incorporating humanoids for practical VR safety assessment (Choi et al., 2015; Sermet & Demir, 2022). Collisions can be detected while comprehensively analysing human/robot intended behaviour (Matsas & Vosniakos, 2017). This underpins the need for a concise database compilation for movements and posture interface to assist in a more realistic DHM representation as Dado desires for future studies (2010). Detecting the intended human behaviour concerning HRC is necessary for accident prevention (Matsas & Vosniakos, 2017). Similarly, Koppenborg et al. plan to improve safety, ergonomics, and productivity through research with results implemented in natural settings (2017). Also, Bhide et al. aim to use physiological measures to improve trainee capability in risk mitigation (2015). Both Nazir & Manca (2015) and Oyekan et al. (2019) expressed the ambition to expand current virtual reality environments (VRE) simulations in various sectors with highly skilled manufacturing activities for training improvements, performance assessments and safety/accident analysis. Another growing application of VR is in the concept of serious games (SG), which are games designed for “serious” purposes other than just entertainment. Uses of SG include education, training, engineering, and emergency preparedness through a sequence of patterns to make learning fun and interesting. The combined VR-SG can thus captivate users’ attention and provide an exciting outcome while using SG, especially during safety assessments. Similarly, VR-SG has proven effective when employed for training in emergency fire evacuations (Feng et al., 2018). These noted imminent works involve improving more comprehensive risk assessment models with active operational factors to grant a more formidable and holistic perception of the human element.

1.6 Research gaps and suggestions

Several research works have explored the applicability of VR in an industrial context. Due to the potential of VR, its use in accident prevention has recently attracted much research. However, few currently exist applications of the technology for accident prevention in the industrial context, especially in the use of high-end, fully immersive HMD. As aforementioned, this study assessed the implementation of fully immersive VR in three safety countermeasures geared toward preventing accidents. Furthermore, rather than emphasizing the safety outcome of VR intervention, applications have primarily focused on the usability of the apps, on the developmental and experimental initiatives, and comparison with traditional safety methods rather than on promoting the safety of the daily work environment and activities. Several applications of VR for improving safety in the manufacturing industry are also presented in the literature. For example, Matsas & Vosniakos (2017) designed a VR application for enhancing mental safety and situational awareness in the automobile industry and concluded with the emphasis on the capacity of the VRTS for experiencing a sense of presence as a phenomenon of situational awareness in the virtual realm coupled to the ability to transfer this knowledge to real industrial work. In fire safety training, Çakiroğlu & Gökoğlu (2019) proposed VR behavioural skills training as they indicated significant improvement in behaviour during an emergency fire by participants.

Regarding EPR initiatives in industrial plants, Longo et al. (2019) proposed a system for real-time VR emergency scenarios. They concluded that the system had an enormous impact on emergency preparedness and could enable managers to brace adequately for factory emergencies. Despite these VR simulation outcomes improving safety in factories and plants, some limitations and gaps require further studies. These are elaborated as follows.

- Firstly, several VR empirical works of literature that address safety in the discipline (e.g., Dado et al., 2018; Feng et al., 2022; Oyekan et al., 2019) concentrate more on the usability of the immersive environment in comparison to traditional safety measures than utilising the technology for any specified safety domain. In other instances, the research design for safety lacked definitive learning theories for assisting and guiding participants towards a focused learning outcome. Although this overly relative concentration is associated with emerging technologies, researchers such as (Nedel et al., 2016; Seo et al., 2021) however emphasise the need for future research in safety interventions to focus the study design on more authentic learning paradigms. Simulating industrial environments with specific processes and activities for safety countermeasures will enable a deeper understanding of the learning outcomes for those industries.
- Secondly, although VR is utilised in simulations purposefully to create a sense of presence in the virtual world, most experiments in this domain fail to access the levels of presence in their studies (Schwind et al., 2019; Zou et al., 2017). These omissions also limit the measure of interactivity and, therefore, the realism of the experiment. A lack of presence measurements in VR simulations also jeopardises industrial applications (Witmer et al.,

2005). In this wise, the current study investigates the sense of presence in VR safety interventions. It includes demanding occupational activities in simulations to increase *involvement* and *interactivity*, which are essential for practical hands-on training assessments.

- Thirdly, VR is commonly employed in research to obtain human behaviour data in fire safety (Çakiroğlu & Gökoğlu, 2019). However, most studies overly focus on the environmental cues during the pathfinding phase. For example, evacuation during a fire in an underground building (Wang et al., 2021). Research on evacuees' performance due to route turning (Zhang et al., 2021). Only a few studies, such as (Fujimi & Fujimura, 2020), explored the pre-evacuation time during a VR emergency fire evacuation. Further studies of pre-evacuation time in immersive environments will help understand the human causes of evacuation delays.
- Fourthly, some participants during VR experiments experience various symptoms of simulator sicknesses in fully immersive virtual environments; for example, motion sickness (Rzeźniczek et al., 2020), cognitive overload, physical discomfort (Altın & Aksoy, 2020), and distracted attention (Lee Chang et al., 2017). That notwithstanding, the majority of VR studies neither take measures to prevent simulator sicknesses nor do they incorporate investigations about this possibility in their research. This prompts the question regarding the need to assess the likelihood of simulator sickness for simulations in experiments that employ the technology.
- Fifthly, despite the benefits of fully immersive VR simulation environments (i.e., better visibility, safer environment, the capability to create riskier and more realistic situations, as well as the potential to customise the risk assessment to specific scenarios, processes, and activities), there is however scanty research designed for improving a factory layout with emphasis on accident prevention(Norazahar et al., 2018).
- Sixth, in fire safety, no attempt has been made, at least in immersive simulations, to investigate the effects of captivating occupational activities on evacuees' reactions and evacuation durations while evacuating from the workplace simulation. This would help assess evacuation durations during emergencies, human behaviour while evacuating and evacuation response time, which is impossible in real-life situations. For example, while comparing the effectiveness of VR training to video training in fire safety, Lovreglio et al. (2021) represented the simulation in an empty room and not under any activity-based work environment or work procedures. Activity-based fire evacuation simulations could improve EPR activities and safety training and increase the sense of presence for participants.

These gaps highlight unexplored areas in applications of the VR technology within the industry for improving safety training, HIRA and safety self-efficacy that could trigger and motivate future works in the selected industries.

1.7 Research objectives and research questions

1.7.1 Research objectives (RO)

The main objective of this study is to examine current evidence of the merits and demerits of VR for preventing accidents during related occupational activities, processes, and work conditions in both a manufacturing factory and a plant maintenance simulation. The study examines relevant research with safety theories and models applicable to VR simulations to achieve this aim. Through immersive simulation models, questionnaires, and interviews, the study investigates the prospects of VR intervention on safety countermeasure in selected high-risk occupational settings where VR utilisation is lacking. The targeted areas are:

- Safety training, with a design that focuses predominantly on fire safety in situational awareness, fire evacuations, and fire control/mitigations from a gas-fired power plant. The training model also considers evaluating the safety and ergonomics of the VR environment and process.
- Conduct a hazard risk assessment for identifying hazards and a qualitative evaluation of the recognised risks with possible control and mitigation measures in the work environment simulation.
- EPR, for preventing accidents, controlling hazards, mitigation plans, fire disaster preparedness and response in the plant simulation.

1.7.2 Research question (RQ)

What factors explain the effective utilisation of VR for improving occupational safety in manufacturing processes and maintenance activities? Effectiveness in this context regards the successful implementation of VR in achieving the intended safety countermeasure, and it was measured by participants' perception of the achievement of the specific safety intervention. The following sub-questions (SQ) are formulated to bolster the central research question:

- SQ 1: What is the effectiveness of employing a VR emergency scenario for hazard risk assessment and mitigation in a manufacturing factory process simulation?

- SQ 2: How effective can a gamified virtual activity be implemented in a plant simulation with work activities for safety training?
- SQ 3: What is the effectiveness of utilising VR for EPR in the plant simulation while conducting a maintenance activity?

1.8 The research design adopted for the study

A mixed research strategy comprising quantitative and qualitative methods was employed with experiments followed by a questionnaire, observations, and simulation data to answer the three SQs above. These methods (detailed in Table 2) were selected to conceptually test the theories and provide an in-depth analysis of the VR for the accident prevention phenomenon under investigation. Figure 1 explains the main research question from the three SQs, designed to meet the research objectives. These SQs are further addressed with the publications indicated in the Figure. Furthermore, Table 1 presents the individual goals and RQs of the five publications included in the study.

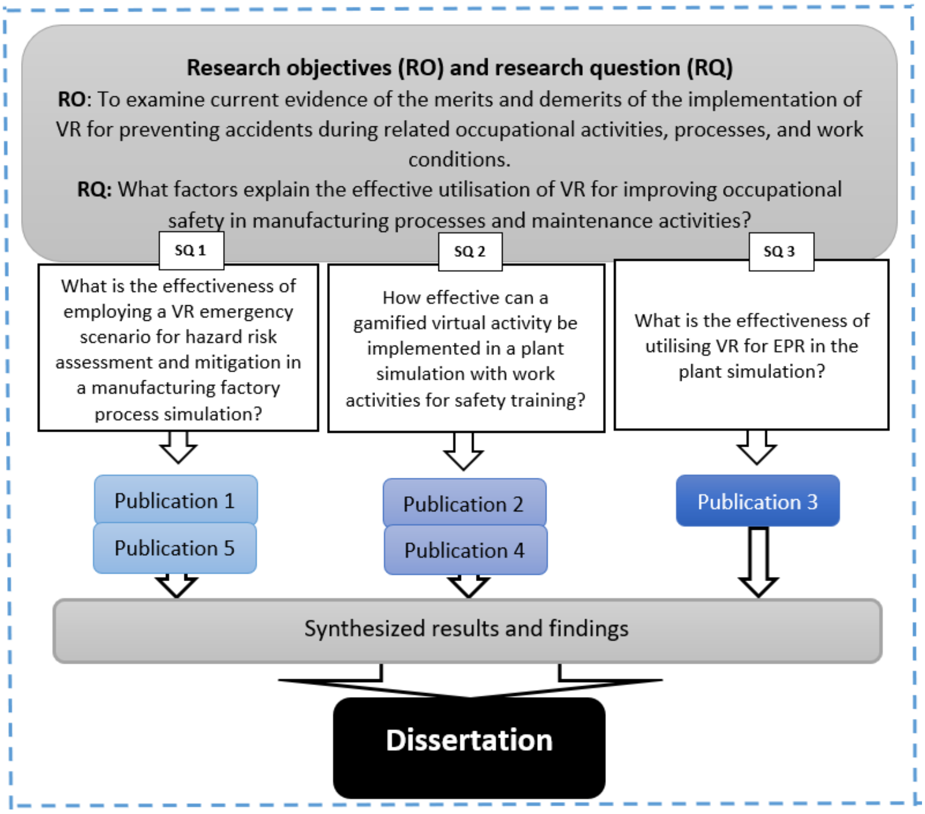

Figure 1. Research design

Thus, by the answers provided in the separate publications, the study intends to meet the primary RQ while contributing to the theory of VR for safety improvement in the selected industrial setting.

Table 1. Components of each publication

Publications	Objectives	Research questions
Publication 1: Optimising Occupational Safety through 3-D Simulation and Immersive Virtual Reality	This study employed the workplace safety checklists (WSC) to verify the applicability of VR for identifying hazards in a manufacturing process simulation. Secondly, it measured participants' perception of the closeness of the factory process simulation to reality.	What are the prospects of conducting a hazard risk assessment exercise to identify hazards in a VR factory simulation? How close can the simulation be to an actual factory regarding production processes, layout configurations, and equipment dynamism?
Publication 2: Simulation-based Safety Training for Plant Maintenance in Virtual Reality	This preliminary study determines whether evacuation and mitigation training in a VR-SG is viable in a plant simulation during a maintenance activity.	How close to a gas-fired power plant can a 3D simulation be for safety training? How effective can a VR-SG-designed maintenance activity be in a plant simulation?
Publication 3: Simulation-based assessments of fire emergency preparedness and response in virtual reality	To understand if the gas-fired power plant simulation can adequately display hazards for situational safety awareness in VR. Also, to verify if the plant simulation is safe for EPR in VR.	What measurement of safety situational awareness can be achieved in a gas-fired power plant simulation for detecting a fire hazard? How effective and safe can a gas-fired power plant 3D simulation be for an EPR exercise in VR?
Publication 4: Effects of an engaging maintenance task on fire evacuation delays and presence in virtual reality	To investigate the effects of engaging occupational maintenance activities on the response time for evacuation in the event of a fire emergency. Besides, the aim was to verify whether the maintenance activities during the fire emergency correlate with a higher sense of presence.	What effect does an engaging maintenance activity have on the pre-movement duration during a fire emergency in a gas-fired power plant simulation? What relationship does a maintenance activity in the plant have on the sense of presence in the simulation?

Publications	Objectives	Research questions
Publication 5: Factory Layout Design and Optimization Focusing on Accident Prevention	To experiment with designing and optimising a manufacturing process simulation in 3D. Secondly, to assess the possibility of conducting a hazard risk intervention for hazard mitigations.	How much improvement can be realized in the factory through VR scrutinization of the 3D manufacturing processes, and what type of hazards can be identified for mitigation in the simulation?

1.9 Significance of the study: Why is the study necessary?

This dissertation fills the gaps mentioned above in the literature by explaining the importance of various findings regarding the effective utilization of fully immersive VR in safety countermeasures. Thus, emphasizing the contributions to new knowledge while highlighting the benefits in future research by the following:

- Firstly, the study contributes to VR research for safety improvement, as demonstrated in other industries where utilization of the technology has matured. For example, in construction engineering (e.g., Seo et al., 2021). In this research, it was to demonstrate that participants in a factory/plant simulation can experience a real-time encounter with interactions and receive responses necessary for safe evacuation training, HIRA and EPR.

- Secondly, the study shows that realistic emergency scenarios can be generated in VR simulations for real-time encounters that are needed in experiential learning during fire evacuation training. Such virtual interactions can influence safety decisions at the factory and plant conceptual stages.
- Thirdly, specific hazards can be generated in the simulations while engaged with demanding occupational activities to highlight the essence of safety situational awareness in a plant or factory simulation.
- Fourthly, the study explicitly illustrates that a captivating maintenance activity in a plant simulation increases presence in a VR simulation environment, which is a factor necessary for VR hazard risk identifications and safety training.
- Fifthly, the study signifies that 3D simulations in VR can adequately represent emergency fire situations for evacuation assessments from a performance-based fire safety engineering facility.

1.10 Dissertation structure

The dissertation is divided into two main parts: The first part constitutes the six chapters of the research summary, while the second contains the research publications. The first part is explained below.

- Chapter 1: Introduction to the purpose of the study, emphasizes the background, literature regarding the progress, technologies with industrial applications, research gaps, the focus of the current research and scope. The aims and objectives are also explained here.
- Chapter 2: This chapter presents the theoretical background, including the salient theories, models, and constructs employed in the dissertation.
- Chapter 3: Here, the research methodology is described, which explains the VR setup, experiment process, data collection techniques, data analysis and statistical analytical methods with the reliability and validity for repeatability.
- Chapter 4: A summary of all the five publications employed for the dissertation is presented here, emphasising the results and findings.
- Chapter 5: Chapter five synthesises the results and findings as well as limitations, contributions, recommendations, and managerial implications.
- Chapter 6: This chapter concludes the dissertation with emphasis on the new knowledge and the relevance of the entire study.

2 THEORETICAL FOUNDATION

This section discusses the intellectual cornerstones of the scientific background embraced in the logic of this dissertation, which is focused on accident prevention.

2.1 Related concepts

Several related concepts and theories to safety practices for accident prevention have been established. This section presents the salient definitions of the basic safety parameters employed in this dissertation.

2.1.1 Occupational Hazard

In occupational safety, a hazard is a source capable of causing damage, harm,r adverse health effects on a human or something (Ramesh et al., 2017). Hazards cause increased liabilities, production losses and injury to people and organizations (Covello & Merkhoher, 1993). In accidentology, harm can be caused by accident due to exposure to a source of hazard. According to Rout & Sikdar (2017), the categories of risks are any king of unsafe working conditions with the possible release of potential energy to cause injury (physical, emotional or psychological pain), property damage or death. The most prevalent hazards in manufacturing and process industries are safety hazards. Safety hazards include potential sources of slips, trips, falls, and machines without the appropriate guards. This dissertation, however, concentrates on preventing accidents and near misses under the safety “physical” hazard category, which comprises: Electrical, ergonomic, fire and explosion, heat, noise, radiation exposure, and subjection to excessive vibration. For this reason, the following other types of hazards are not considered in the study: Biological, Chemical, and Psychosocial.

2.1.2 Hazard control

Hazard control refers to measures instituted to reduce the possibility of harm caused by a hazard (Kjellen & Albrechtsen, 2017).

2.1.3 Hazard identification

Hazard identification refers to the recognition of a hazardous situation or circumstance that has the potential to lead to an accident in a specified environment (Kjellen & Albrechtsen, 2017).

2.1.4 Risk

The ISO 45001 standard defines risk as the effect of a situation which involves exposure to danger. *Therefore, risk is the likelihood of harm*(ISO 45001: 2018).

2.1.5 Risk analysis

Risk analysis is a process where a risk perception is determined by the consequences and probability of undesired incidents (Kjellen & Albrechtsen, 2017).

2.1.6 Risk assessment

The assessment of the consequential severity that an identified harm could cause considering the level of exposure and the likelihood of the harm to an individual, people or the environment. Therefore, risk assessment describes the entire process of hazard identification that has the probability of causing harm. Risk assessments also evaluate and analyse the damage associated with a particular hazard. This is termed risk analysis or risk evaluation, and it is the most suitable means of eliminating the threat or mitigating the risk in the likely event of its occurrence (Covello & Merkhoher, 1993; Norazahar et al., 2018).

2.1.7 Risk management

Risk management is the complete procedure for identifying and counteracting a hazard within a specified environment and work process to prevent injuries or accidents (ISO 45001:2018). Risk management provides a structured and logical framework for handling hazards. In risk management, the potential effects of risks are evaluated to assess the most effective system and measures for preventing their occurrence (Dali & Lajtha, 2012).

2.2 Accident causation theories

Accident theories are a system of ideas, assumptions and fundamental principles designed to explain the underlining factors for the causes of accidents; termed accident causation models (ACM). (Hopkins, 1999). ACMs are intended to limit and prevent fatalities, injuries, environmental effects, and property loss (Kjellen & Albrechtsen, 2017). Furthermore, accident causation theories seek to explain the underlining causes of accidents and preventive measures (Din & Gibson Jr, 2019;

Hovden et al., 2010). Several types of ACM exist for identifying and analysing risk factors.

2.2.1 Types of ACMs

The International Electrotechnical Commission (IEC) 61025:2006 standard (International Electrotechnical Commission, 2006)categorises accident models into two types. The traditional static ACMs and the dynamic (non-linear) ACMs. Both models aim to understand the details of accidents and the subsequent development of intervention methods. While the static ACMs analyse static data in a linear sequence to identify the underlining causes of accidents, the dynamic ACMs, on the other hand, access accident causations with continuous flow, having a combined influence on accident causation (Li et al., 2017). These models in Figure 2 further propose appropriate corrective and preventive mitigation measures for accident avoidance, detection and investigation at particular instants or through static data analysis. Static models, however, are not employed for analysing dynamic events consisting of multiple factors acting concurrently and time-dependent behaviours of the accident-causing systems and processes, which are within the capability of dynamic ACMs (Dhalmahapatra et al., 2020). The traditional static ACMs include the accident proneness theory, the Domino theory and the Epidemiological theories. Dynamic ACMs, on the other hand, include the dynamic hazard and operability studies (HAZOP), Monte Carlo simulation (MCS) and dynamic fault tree analysis (FTA). State-of-the-art dynamic ACMs utilise 3D simulations with immersive and interactive VR for enhancing safety training and hazard risk assessments (Dhalmahapatra et al., 2021).

2.2.2 Fundamental accident theories

Most of the accident-causing theories are derived from three fundamental ACMs. These form the basis for accident investigation and feedback for designing methods and tools for safety management. These models are:

- Heinrich's domino theory of accident explanation is the first scientific approach to accident investigation, which analyses accidents caused by unsafe acts, carelessness, and poorly designed or unmaintained equipment (Heinrich et al., 1980).
- Gibson's energy barrier theory (1961) explains that accidents are caused by a transfer of energy flow from one state to another, resulting in a disaster. This theory demonstrates the use of barriers to prevent energy flow(Gibson, 1961).

- Haddon (1973) explains the ten strategy theories for loss prevention.

These pioneers converge on the notion that the prevention of accidents largely depends on understanding the causes. The main variations in accident theories are the differing views of the accident phenomenon (Hovden et al., 2010). Several ACMs have subsequently evolved, and below are seven widely used theories for accident prevention, investigation and safety training. In several instances, one theory is insufficient for a typical accident investigation as experts in the field hardly rely on only one theory. Combining accident theories is the basis for current accident models applicable for accident prevention. This combination idea is also called the Combination theory.

- Process theory: The process model presents an accident as a deviation from normal to cause harm such as injuries or loss of control.
- Logic tree theory: As a logical sequence of relationships in events and conditions that causes an accident.
- Human factor theory: Accidents are caused by a string of events due to human error with three factors: Overload, inappropriate response, and incorrect activities.
- System theory: Several factors for combining elements, including human, organisational, and technical. Includes models such as the management and systemic models that examine the dynamism of accident causations. The systemic accident models explain that the causes of accidents do not occur in isolation but that several factors (failures) contribute to the systemic environment and are not solely based on human failure (Yousefi et al., 2019).
- Cognitive theory: considers accident causations primarily based on failure in cognitive function.
- Causal-sequence theory: Accidental events leading to injuries or losses.

2.3 The Generations of ACMs

Khanzode et al. (2012) categorised ACMs into four generations in their comprehensive occupational injury and accident review. Later, researchers such as Fang et al. (2016), Maruyama et al. (2018) and Dhalmahapatra et al. (2020) grouped ACM into five generations, with the fifth utilising computer modelling and 3D simulations, which subsequently placed VR applications for safety countermeasures in the fifth generation.

2.3.1 The First-generation ACM

The first-generation ACMs are known as accident proneness theory, as categorised by Khanzode et al. (2012. These are based on primitive views such as "acts of gods" and place accident causation on situational behaviour, inherent personality, and individual characteristics. For example, studies at the time, for instance, Greenwood & Woods (1919), Greenwood & Yule (1920) and Kunce (1967), explain that the accident proneness vulnerability criteria according to this theory are human factors such as inexperience, attitude, stress, and age. This view is also held by Fu et al. (2020). They categorised the first-generation ACM with the accident proneness theory and traced accident responsibility to human characteristics and situational behaviour (Greenwood & Woods 1919). This theory suggests that about 20% of people are prone to accidents.

2.3.2 Second-generation ACM

The second-generation ACM defines the causes of accidents on a sequence of events that trigger accident occurrence; termed the domino theory. The theory was developed by H. W. Heinrich et al. (1932, suggesting that a chain of events called dominos causes accidents. The dominos include human error, unsafe acts, physical hazards, unsafe work conditions, ancestry, and social and environmental factors (Heinrich et al., 1980; Lehto & Salvendy, 1991). Although the domino theory is old, it is still employed with other industry ACMs for accident prevention and mitigation (Pasman et al., 2018). Following these developments, W.G. Johnson developed the management oversight and risk tree (MORT) model (Johnson, 1973). MORT was designed with a technique to investigate accidents with various safety concepts. Several other theories like the fault tree model (Tanaka et al., 1983), stair-step model (Heinrich et al., 1980), the event tree, and causal tree models were developed with the sequence of events that leads to an accident (Katsakiori et al., 2009). Another ACM that is also framed on Heinrich's human error theory is the Tripod ACM method, which suggests that accidents occur due to human errors by failing to maintain barriers for "blocking" underlining accident causation events (Gower-Jones et al., 1998). These were followed by the barrier analysis models (Lehto & Salvendy, 1991) that formed the Swiss cheese theory. For example, the US Department of Energy developed the Target-Hazard-Barrier analysis model in 1996. This theory explains that there are three elements in the barrier analysis. These are the target, the hazard, and the barrier (Khanzode et al., 2012).

2.3.3 Third-generation ACM

The foundation of the third generation ACM is credited to James Reason's "Swiss cheese" accident causation theory (Reason, 2000), which illustrates the occurrence of an accident linked to a series of underlining events and conditions. Gower-Jones et al. (1998) explain that the circumstances and conditions are associated with systems, machines, or process failure. For example, the sequential timed events plotting (STEP) and the multi-linear event sequencing (MES) methods are models that sprang up in 1975 (Pasman et al., 2018). These are employed in accident investigation and analysis to explain the connecting events that prompt an accident. Several other ACM linked to the Swiss cheese model was developed for risk assessment and safety management. For example, Shappell and Wiegmann's Human factor analysis and classification system (HFACS) was designed for analysing and investigating human involvement in accidents (Shappell et al., 2007).

2.3.4 The fourth-generation ACM

According to Düzgün & Leveson (2018), the fourth-generation ACM is related to causal analysis and relies heavily on the systems theory. Kjellen & Albrechtsen (2017) explain that the systems theory considers accidents due to the dynamic complex causal relationship between humans, technology, and organisational systems and not on a simple chain of events. For example, a road accident can be classified as a failure of the entire traffic system comprising the interaction between the driver, the vehicle, road infrastructure and the weather. Hollnagel's cognitive reliability and error analysis methods (CREAM), which identifies mental activity and conditions for accessing human performance consequences, is an example of systemic ACM (Hollnagel, 1998). Perrow's Normal Accident theory about the unavoidability of accidents established on multiple and unexpected failures of complex societal systems is another ACM in this category (Perrow, 2011).

2.3.5 Fifth-generation ACM

As Maruyama et al. (2018) and Dhalmahapatra et al. (2020) have discussed, dynamic ACMs utilise modelling and simulation (Figure 4) for modifying static accident scenarios to capture the dynamic and time-dependent behaviours of events and circumstances leading to failures that cause accidents. Despite the benefits of traditional ACM (the previous four generations) as discussed in section 1.2, several researchers have enumerated limitations (as listed below) which have triggered the introduction of the fifth generation of ACMs. These models introduce advanced technology with real-time 3D visualisations, and realistic accident scenario encounters into existing ACMs and safety management theories.

- Traditional ACM is established on the relationship between cause and effects and does not incorporate adequate hazard presentation with situational visibility for responses necessary in experiential learning.
- There is limited exposure to emergencies as the status co still depends on classroom learning or on-the-job training, which cannot subject people to natural hazards for assessment or training purposes.
- Classroom safety training is passive and tedious as there is limited engagement in the learning subject.
- Retention of the subject matter to participants is minimal as learning does not usually involve practice and actions. (Dhalmahapatra et al., 2021; Y. Feng et al., 2022; Zhou et al., 2022)

Secondly, the introduction of intelligent machines coupled with increasing automation and robotisation in this age has prompted the introduction of technological advancement to accident theories. Although VR-based ACMs also have a fair share of limitations for safety countermeasures, as listed below, there are several benefits in its application which have spurred growth in high-risk occupational settings, as aforementioned in the introduction. Accordingly, 3D dynamic ACMs incorporating VR have been growing in the last decade due to the advantages of the technology when compared to the static ACM counterpart (Dhalmahapatra et al., 2020; Nazir & Manca, 2015). VR can intuitively access real-time situations necessary for user interactions while experiencing the accident phenomena (Lanzotti et al., 2020). Similarly, VR safety models are immersive and essential for creating exciting experiential learning environments and encounters (Bordegoni et al., 2022; Hussain et al., 2020).

On the other hand, VR enhances hands-on learning in project field trips. While immersed, participants are involved in an experience both physically and perceptually. Likewise, Bricken (1991) states that VR technology is a tool for experiential learning in situations that can not be purposefully created for safety assessments, like in an emergency factory fire scenario. Brown et al. (1989) proposed a VR-based situated learning model which explains knowledge to be situated and combines the culture, activity and context that is developed for utilisation. For this reason, several researchers in the discipline, for example, Mujber et al. (2004), Nazir et al. (2015) and Sermet & Demir (2022) have reported from empirical evidence that VR can present process concepts in more realistic and understandable ways for safety countermeasures than traditional training methods like videos, PowerPoint presentations, and 2D CAD representations. For this reason, applications of the fifth-generation ACM for safety countermeasures are increasing in some high-risk occupational settings (Bordegoni et al., 2022). For example, the dynamic simulation-based HAZOP has been used by Tian et al. (2015) to analyse deviations in active operations for enhancing risk assessments during extractive distillations in the chemical industry.

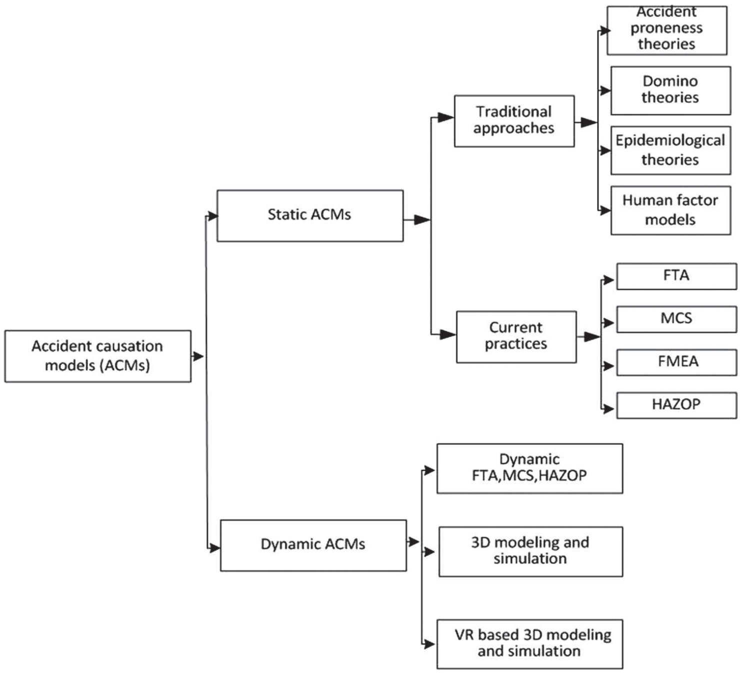

Figure 2. Static and dynamic ACMs. *Cited* from Rajkumar et al. (2021)

2.4 The VR concept

An immersive VR is a computer-generated technology that engages and replaces a real-world environment with real-time 3D virtual environments, objects, sounds, and dynamisms (Berg & Vance, 2017; Morley et al., 2015; Rozenfeld et al., 2010). The VR concept was coined in 1989 by Jaron Lanier when the technology began to gain acceptance in research and for psychiatric treatment (Conn et al., 1989; Gorini & Riva, 2008).

Ivan Sutherland is credited for creating the first fully immersive HMD to display a computer-generated image at the Lincoln Laboratory, Massachusetts Institute of Technology, in the 1960s (Budziszewski et al., 2016; Sutherland, 1965). VR images in an HMD are stereoscopic, implying a slight difference in the pictures displayed to both eyes to simulate a spatial vision impression. Fully immersive VR simulations provide the user with the highest possible realism with real-time natural senses. Usually, sight, touch, and hearing. Multisensory VR technologies incorporating olfactory and thermal sensors with more heightened realism are also emerging (Shaw et al., 2019). Interactions in HMD virtual environments are possible using hardware devices such as controllers and tracking gloves. VR tracks a user's head, hand movements and position to adjust with sight depending on the viewing angle. Accordingly, the user's senses connect to the virtual world through a computerised application to provide a sense of presence for interacting with the simulated world (Lawson et al., 2016). Users immersed in a virtual simulation become convinced of the reality of the created objects, situations and processes to act and receive instant sensory responses (Sekaran et al., 2021). Accordingly, the VR concept provides a platform for experiential learning, which has several benefits for enhancing industrial safety (Alrehaili & Osman, 2019; Jin & Nakayama, 2013).

The dynamic ACMs, as presented in Figure 2, constitute the HAZOP, the MCS and the FTA. These models are implemented in a 3D modelling and simulation to deliver the specific accident phenomenon to immersed participants in a VR-based environment.

2.4.1 Experiential Learning Theory in VR

The theory of experiential learning, according to David Kolb, is a training process through the transformation of experience (D. A. Kolb, 1981). Whereas static ACMs emphasise behavioural and mental processes while ignoring the role of experience in the learning processes, experiential learning depends heavily on encounters, emotions, and cognitive and environmental factors in the learning process (Alrehaili & al Osman, 2019; A. Kolb & Kolb, 2018; D. A. Kolb et al., 2014). Alrehaili & Osman (2019) explain that VR provides the possibility to experience a replica of a specific process, condition, and environment, which places it at the "simulation of a real experience" on Edgar Dale's pyramid of learning in Figure 3.

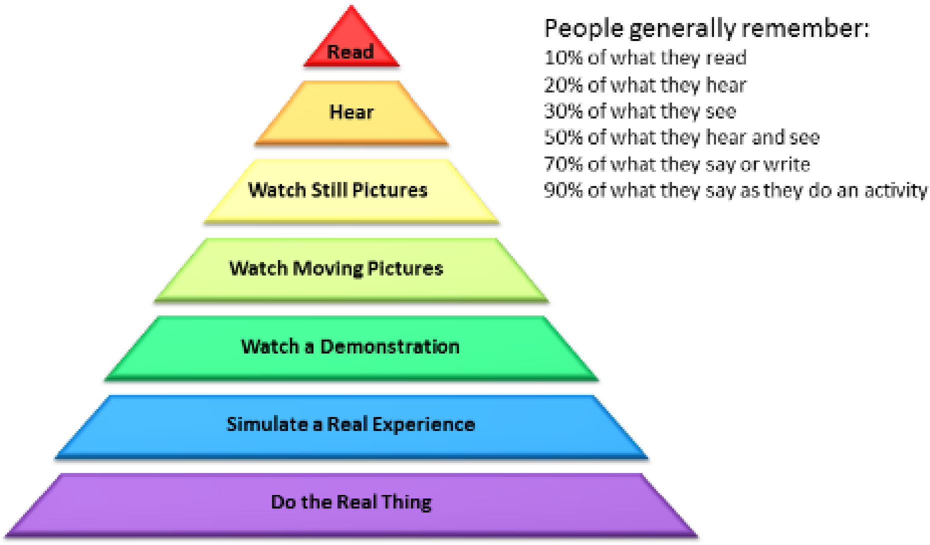

Figure 3. The learning pyramid: *Cited from Parallax Education (2017)*

2.4.2 VR for safety intervention

Simulation-based technologies for improving occupational safety have impacted high-risk industries such as construction and mining in recent years (Choi et al., 2015; Getuli et al., 2020). Zhou et al. (2022) also explain that the application of current technologies like VR, building information modelling (BIM), and the 4-Dimensional computer-aided design (4D CAD) have been utilised in safety models for hazard prevention in the construction industry.

2.4.3 VR-ACMs

Further development of the dynamic 3D ACM by incorporating VR for safety management is the basis for the VR-ACM. Dalmahapatra et al.'s (2020) model illustrate the main features of the VR-ACM in Figure 4. The immensity of the VR-ACM employs the systems theory of accident causation by focusing on the factory environment, manufacturing processes and human activities to analyse the underlining conditions which cause accidents. This theory is predominantly utilized in this dissertation in a closed-loop model for participants to respond to emergencies (during the fire evacuations) and corrections for the deviations between the simulated and the desired states (during the HIRA). According to Bhide et al. (2015), other safety paradigms that have experienced VR-ACM for safety intervention include HIRA, ergonomics evaluations, and EPR.

2.4.3.1 Modelling and simulation of virtual objects

The first part of the VR-ACM constitutes modelling virtual objects and simulation of 3D dynamic activities. The VR concept replaces the natural environment with the artificially generated one to relate and interact with the virtual environment (Sermet & Demir, 2022).

2.4.3.2 Accident causation scenario

The second part of the VR-ACM is the accident causation section. Both static and dynamic accident conditions and scenarios are presented to participants for realistic visibility, audibility, and interactivity in the VR environment. Examples of accident causation conditions are; slippery floors, unprotected sharp objects, crashes with moving machinery, and collision possibilities with robots (Heinrich et al., 1980; Kjellen & Albrechtsen, 2017). Risk control measures for accident prevention and mitigation have been implemented in the virtual realm to visualise possible safety countermeasures (Spearpoint & Hopkin, 2020). During factory design stages, remediation and inspection of a simulated facility for safety considerations such as unsafe pathways in the layout and emergency evacuation possibilities can be evaluated (Bordegoni et al., 2022).

2.4.3.3 Virtual reality safety training

Safety training aims to equip trainees with the required knowledge, skill, and competencies for performing work procedures safely and effectively. McGovern et al. (2020) and Seo et al. (2021) emphasise that safety training provides comprehensive knowledge to enhance skills, behaviour, motivation, and attitudes necessary for preventing and mitigating risky accidental situations (McGovern et al., 2020; Seo et al., 2021). Hale's comprehensive framework for safety training includes hazard recognition, appropriate decision making, work procedures, and execution of safety actions (Hale, 1984). VR safety training theory is based on a high level of interactive engagement and an experience of reality in the virtual realm. During VR-based training sections, users become acquainted with the reality of a simulated environment, system and machinery for practising several operations before being subjected to an existing facility. Models are designed to equip participants with situational experiential capability during immersive exercises (Bordegoni et al., 2022). According to (Kinateder et al., 2014; Spearpoint & Hopkin, 2020), the success of VR for training is attributable to the level of presence experienced in the virtual environment. These features also motivate users to pursue personal safety practices for confidently tackling industrial safety procedures (Oyekan et al., 2018) (Dhalmahapatra et al., 2020).

2.4.4 VRTS

HaiyanXie et al's. (2006) VRTS safety-training model analyses behavioural and perceptual situational outcomes while training construction workers. The VRTS that have emerged for specific industries include Haller et al. (1999), VR-based safety training system for an oil refinery. Likewise, Dhalmahapatra et al.'s (2020) conceptual framework in Figure 4 shows the three distinct parts of the VR-ACM: VR modelling and simulation, generating an accident causation scenario, and safety training. It serves as the development of the framework for this dissertation. Other application examples of VR for safety training include Morélot et al. (2021) procedural knowledge and skill acquisition while evaluating the impact of the immersion with the levels of presence in the virtual realm, and Egaji et al. (2022) VR-based safety skills enhancement for a railway crossing. Also, Määttä's (2007) model for safety analysis with virtual environments (SAVE) and participatory ergonomics (PE) has been validated to evaluate work safety analysis (WSA)(Määttä, 2007).

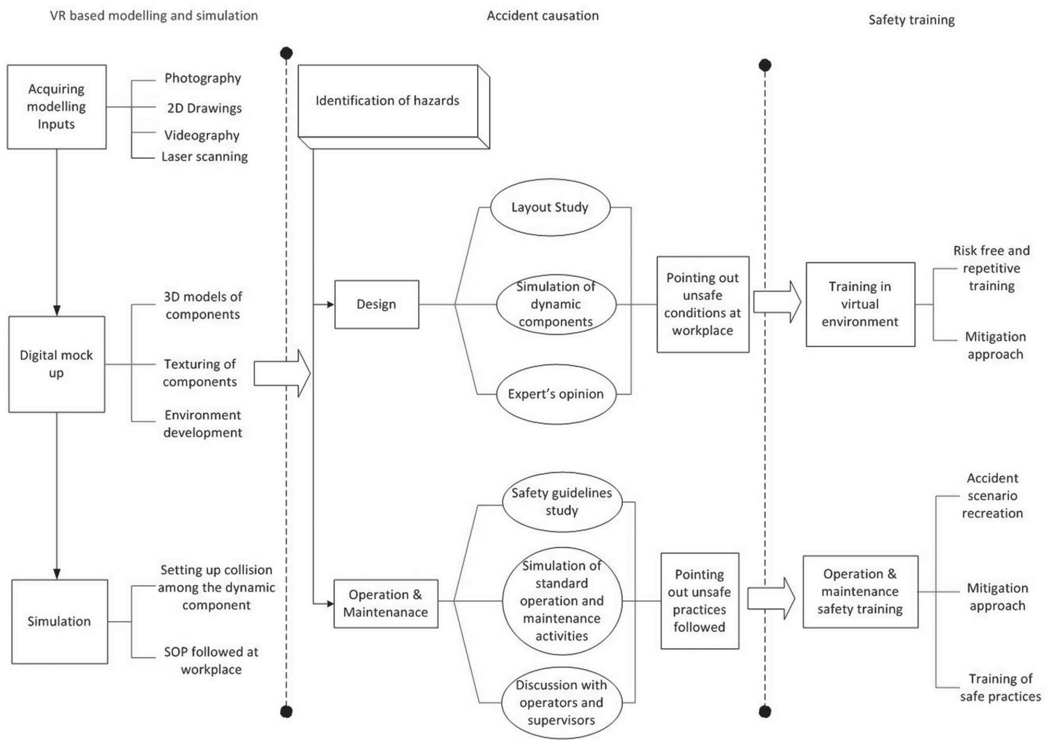

Figure 4. Structure of the VR-ACM. Cited from Dhalmahapatra et al., (2020)

2.4.4.1 VRTS for Human-Robot collaborations

Matsas & Vosniakos (2017) and Oyekan et al. (2019) have developed a human-robot collaborative model for assessing the capability to enhance safety while working with robots and during manufacturing activities. Matsas & Vosniakos's model promotes situational safety awareness and mental safety with a serious-games (SG) concept. Their model provides a platform for transferring the safety knowledge gained in the virtual realm to an actual industrial activity, which underpins the notion that situational awareness can be enhanced through the experiential learning platform that VR provides. Moreover, the robot acceptance safety model (RASM) & the human-robot work collaboration (HRWC) models are utilised extensively for the prevention through design (PtD) initiative within the human-robot collaboration (HRC) safety systems (Matsas & Vosniakos, 2017).

2.4.5 VRTS for EPR

EPR is an approach to disaster preparedness and the appropriate actions necessary for mitigating the effect of a disaster in fulfilling the requirements of the standard for management systems of occupational health and safety (MS-OHS) (ISO 45001:2018). This model is based on Deming's Plan-do-Check-Act concept with a user-centred learning experience Karkoszka (2020). On the other hand, Longo et al. (2019) designed a VRTS for industrial emergency preparedness and response. Another virtual reality-based behavioural skills training (VR-BST) model by Çakiroğlu & Gökoğlu (2019) is designed to impart behavioural skills to trainees during fire emergencies. These models have been employed by Lovreglio et al. (2021) for comparing VR fire extinguishing training with video training, with results that emphasise that the VR training model provides better knowledge acquisition than video training.

2.4.6 VR-HIRA Theory

In HIRA, realistic scenarios, improved user engagement, repeatability, and improvement in retention are the salient features of the technic for industrial applications. Dado et al. (2018) designed a VR hazard identification system for training in machine safety. They conducted experiments to assess whether the VR simulator was comparable to traditional hazard identification methods in the operation of a lathe machine. Similarly, Kinateder et al. (2014) designed a VR safety HIRA model for evaluating social influence during fire emergency evacuations. The HIRA model constitutes:

- Work activity classification.

- Hazard identification
- Risk assessment (Analyse the likelihood and severity of the risk as a result of the hazard)
- Apply mitigation measures if the risks are beyond tolerable levels.

2.4.7 VR-SG ACM

Abt (1987) defines the term serious game (SG) as a digital game-based learning (DGBL) environment designed for "serious" applications other than amusement or entertainment Din & Gibson Jr (2019). Accident prevention models at the forefront of simulation-based interventions include VR-SG to boost participants' interest, engagement and focus during training. For example, Smith & Ericson (2009) designed a VR-SG model for training participants in identifying potential fire hazards for safe evacuation from buildings during fires. Chittaro et al. (2018) also proposed a VR-SG for training in aviation safety. Their model tests participants' retention of safety lessons immediately after an experiment and after seven days compared to traditional safety education methods. Results from the participants after the investigation indicated a statistically significant superiority of the VR-SG ACM for safety lesson comprehension and retention over the conventional counterpart.

3 RESEARCH METHODOLOGY

Scientific research practices are governed by well-defined methodologies based on sound principles. These methodologies are rules and procedures for conducting research and evaluating the results (Lindsay, 1951). The initial part of this chapter explains the study's guiding principles (i.e., research paradigms and philosophical stance) and the research approach (i.e., abductive, deductive, or inductive) embedded in the study. Additionally, the chapter provides sound justification of the research methods (i.e., quantitative, qualitative, or a mixture of these two). Furthermore, the chapter explains the methodologies for the experiment setup, procedure, and data collection strategies (e.g., questionnaire, interviews, simulations, case study, etc.) adopted for this dissertation (i.e., risk assessment, safety training and EPR) in the VR conceptual factory and plant simulation models.

3.1 Research paradigms

According to Saunders et al. (2016), a research paradigm is the thinking, a set of shared beliefs upon which an approach for collecting research data is interpreted. A paradigm is also related to how researchers perceive the world, a framework where laws and theories are performed to constitute knowledge. Creswell and Creswell (2017) explain that the variations of these world views are framed from a researcher's recognition of what knowledge constitutes and the ontology of what we perceive (epistemology) that the research methodology should follow (axiology). The paradigm components and philosophical stance of the dissertation are explained below.

- Ontology is a scientific branch of philosophy that examines human nature and seeks to establish reality or truth and how knowledge of what we perceive as authentic can be evaluated. Ontology considers objectivity and assumes the existence of only one fact. In computer science, ontology also refers to representing and defining concepts, properties, and all possible domains. The conscious experience VR provides presents the brain of the technology used with an integrated ontology for interpreting their world in the virtual environment (Metzinger, 2018a). For this reason, Heim's theory describes VR as a computationally implemented ontology (Heim ,1994).
- Epistemology establishes the relationship that exists between humans and our quest for knowledge. What constitutes a justifiable belief and the kind of knowledge available are all related to epistemology. Like ontology, epistemology deals with knowledge study and establishes the difference

between defensible opinions and beliefs. Questions arise about VR-epistemology: How are justifiable beliefs about sensory representations presented in the virtual world? How is the knowledge about virtual objects acquired? What is the justification for the class of epistemic effects within or outside of one's mind? What is the source of knowledge about the elements of a virtual world? (Metzinger, 2018a) This explains the concept of research methodology.

- The methodology emphasises the principles of studying and teaching and establishes how appropriate data for analysis are collected (Metzinger (2018). The methodology philosophy refers to the approaches utilised in interpreting and understanding what reality is. In methodology, the way data is collected and the strategies for analysing are evaluated and explained. In this setting, VR has been implemented as a design research methodology within work environment simulations to allow participants to explore its unique role in creating safety countermeasures.
- Positivism covers the majority of VR for safety research, which learns more about quantitative methods. For this reason, Creswell and Creswell (2017) explain that positivists employ quantitative techniques like surveys, questionnaires, and statistics, while interpretivists prefer unstructured interviews and observations.
- Pragmatism is a philosophical approach that analyses beliefs or theories regarding their practical application (J. W. Creswell & Guetterman, 2019), as a chosen research philosophy in this dissertation, which constitutes realistic situations with actions and real-time reactions for examining resultant consequences.
- In post-positivism, multiple methods are employed for data collection and analysis, allowing researchers to acquire a more holistic perception of the matter under experimentation or investigation. Accordingly, the interpretivist theoretical stance deems it necessary that researchers get acquainted with their participants in research while considering the knowledge of individuals as unique, subjective, and personal (Olusegun, 2015; Sauerland et al., 2004).
- Constructivism is linked to interpretivism, which is related to the qualitative research approach. In this approach, research is related to participants' subjective views, historical, experience and social constructs. Unlike the positivist paradigm, the constructivist neither manipulate subjects nor performs experiments and adapts a subjectivist position that reality is unavoidably subjective. Constructivism adopts the stance of relativism, which emphasises that truth exists in people's minds and understanding (Olusegun, 2015).

- Cognitivism. From the cognitivist perspective, learning involves knowledge acquisition, organisation and application of the information from one's senses to existing experiences in the brain. For learning to happen, a mental phenomenon should occur in the learner's mind through engagement in considerable cognitive processing. Current VR research from this cognitivist line of thinking investigates the influence of visual and auditory representation and the interactivity present in immersive encounters (Bricken, 1991; Driscoll, 2002).

3.2 Research approach and methods

The current sub-chapter clarifies the research design and methods regarding the procedure and approach according to the philosophies employed for addressing the RQs in the five publications that form this dissertation. According to Saunders et al. (2016), each research piece follows either inductive or deductive reasoning, regardless of the research paradigm or philosophical stance. A deductive approach usually begins with a social theory and tests the resultant implications with data. In other words, they go from a general to a specific level. At the same time, inductive reasoning is more convenient when the research goal is to develop general principles to explain the observed phenomena.

Regarding the methodology, prior VR simulation experiments in accident prevention have mainly used quantitative methods (e.g., Kinateder et al., 2014; Matsas & Vosniakos, 2017; Longo et al., 2019; Lovreglio et al., 2021), qualitative methods (e.g., Dhalmahapatra et al., 2020; Oyekan et al., 2019) or mixed methods (e.g., Gamberini et al., 2003; Morélot et al., 2021; Vasudevan & Son, 2011). Quantitative methods are usually deductively approached and emphasise quantitative and statistical measures for data collection and validity (Radianti et al., 2020). Quantitative methods also seek to establish relationships between data sets for quantifiable conclusions (J. W. Creswell & Guetterman, 2019).

3.2.1 Justification for adopting mixed method research

Mixed methods employed in research (i.e., a combination of quantitative and qualitative methods) provide a holistic understanding of the research problem under investigation. Although few VR research uses mixed methods, applications appear to increase in recent years. Mixed methods provide detailed contextualized insights with complementary benefits of both approaches while mitigating the weaknesses of the other. As the ROs of this dissertation required experimentation to answer the RQs, the idea of pragmatists (as explained earlier) plays a salient role in the experimentation design. In pragmatism, the researcher's insights are derived from practice-oriented assumptions, real-life scenarios, and the consequences of actions (W. J. Creswell & Creswell, 2018). As the bedrock of VR simulations, pragmatism seeks to evaluate complex theories by actively experiencing existing or conceptual situations, events, and processes in digital models. Accordingly, this dissertation employs a mixed-method with a pragmatist and positivist research approach for the experiments towards accident prevention in a factory and a plant simulation (Table 2). Specifically, publications 1 and 5 included mixed methods, while publications 2, 3 and 4 were purely quantitative (Table 2). Utilizing a mixed-method design in publications 1 and 5 was to obtain different perspectives from participants to answer SQ1 and understand the specific requirements in achieving a well-scrutinized factory layout simulation with inherent risks mitigated to ensure adequate workplace safety.

3.3 The VR philosophy and application in this study

Metzinger (2013) emphasises that VR technology provides the closest metaphor for generating a conscious experience that presents a consolidated ontology. The concept of ontology is not represented only in philosophy for researching the semantics and logic of theories but also in conceptual relationships, data, and domain possibilities. VR can create ontologies while integrating situations into models by constructing experiential scenarios on participants by performing physical activities in the interaction domain. Bricken's (1991) immersive theory suggests that VR provides a constructivist paradigm enabling educational and training concepts necessary for skill enhancement. Furthermore, Bricken (1991) emphasised that in VR, learning is intuitive and experiential, explaining that the phenomenal state provides the essential interactivity configurable for specific learning and training contexts. Such technology features imply suitability for creating realistic patterns of artificial consciousness.

Additionally, Metzinger (2018) explained that VR's artificial consciousness realises synthetic phenomenology, the cognitive change of an immersed person's knowledge state. This creates a neural correlate of consciousness in highly advanced VR systems that incorporates multisensory interface sensations with ultra-high resolutions and real-time responses. Such advanced technology contributes towards achieving amnestic re-embodiment while immersed in the simulation. Amnestic re-embodiment occurs when participants lose consciousness of their physical location and think they are in the simulation. Metzinger (2017) further theorised that the confabulation and delusion of the mind during immersion have epistemic benefits and, therefore, count as a minimised epistemological perspective. Thus, VR has been identified to philosophically include experimental psychology and cognitive neuroscience, which is regarded as a theory from a metatheoretical perspective (Metzinger, 2018a).

Table 2. Research paradigms employed in this dissertation

Philosophy Ontology Epistemology Technology	Positivism, Constructivism, Cognitivism and Pragmatism Singular or multiple realities Exploratory research Fully immersive and interactive virtual reality simulation (Audio-visual)				
Publications	1	2	3	4	5
Methodology	Mixed	Quantitative	Quantitative	Quantitative	Mixed
Experimental methods	Within-subjects	Preliminary study	Between-subjects	Between subjects	Within-subjects
Approach	Inductive	Deductive	Deductive	Deductive	Inductive
Research design	VR simulation preliminary	VR-SG simulation	Experimental VR simulation	Experimental VR simulation	Experimental VR simulation
Data collection	Questionnaire & interviews	Questionnaire	Questionnaire	Questionnaire, observations & simulation data	Questionnaire, discussions & simulation data
Participants	(19)	(38)	(54)	(52)	(23)

3.4 VR simulation experiment setup

As explained in the theoretical foundation of this dissertation, the principal theory employed in individual VR studies includes factory modelling, process simulation, accident scenario, and safety drills. The five studies that sum up this dissertation on the digital manufacturing concept were all VR simulation-based for accident prevention in the VR-ACM design, which involved modelling and simulation, accident scenario, and safety training or hazard-risk evaluation. Publications 2, 3 and 4 employed Bhide's virtual fire safety and emergency evacuation training model with the VR-ACM to equip participants with the requisite skills necessary for emergency fire evacuation. Bhide's model constitutes the creation of the virtual environment, experiential learning, and evaluation of the effectiveness of the training (Bhide, 2017). The methods utilised for the individual studies are presented in Figures 8-13 in the summary of publications below.

3.5 Participants selected for the immersive experiment

In publication 1, 19 participants (i.e., nine from the manufacturing and production industry and ten from research and educational institutions with a minimum of a year of industrial work experience) performed the immersive hazard identification according to the workplace safety checklist (WSC). In publication 2, 38 university student participants with some work experience were involved in the training. Following the immersive training, these participants provided quantitative data for assessment. Similarly, publications 3 and 4 consisted entirely of university student participants totalling 54 and 52, respectively, who performed the maintenance activity and emergency evacuation assessment and subsequently responded to the questionnaires. However, 87% of the participants in publication 3 partook in the experiment for publication 4. With publication 5, eight project stakeholders comprising managers, project engineers, university professors, and researchers evaluated the simulation. These provided qualitative feedback for improving the factory layout, while 15 university students undertook the JSHIRA and hazard mitigation procedure.

Consistent with applicable regulations (Wendler, 2012), all the participants of the five studies signed an informed consent form before immersion. However, ethical reviews were not required since the study designs did not fulfil any prerequisite factors necessary for acquiring an ethical consideration as outlined in the Finnish Advisory Board on Research Integrity (TENK, 2019). Since participants are wholly immersed in fully immersive VR simulation environments, any possible psychological or physical harm in the form of simulation sickness to participants was considered and measures instituted for reduction or possible elimination. These measures consisted of the duration of exposure and the correct adjustment of the HMD on each participant to prevent blurred images, which constitute cyber sicknesses. Besides, the researcher of this dissertation supervised each immersion and guided participants to prevent crashing unto objects in the laboratory.

3.6 VR simulation equipment

Both simulations used for the safety assessments were designed and developed at the Technobothnia VR Laboratory, Vaasa, Finland. The GPP simulation model was created with the Unreal engine version 4.2 (UE4) and Autodesk Fusion 360 engineering and manufacturing software version 2.0.9305. On the other hand, the LIB manufacturing factory model was designed mainly with version 4.0 of the Visual Components (VC) 3D modelling and developing software and SketchUp version 4.2.1 for modelling machines not available in the VC library. A windows ten computer (ASUS, Taiwan) running on an intel core i7 dual-core processor at 3.6GHz speed powered both simulations. The computer had a 32 GB RAM (GTX 1070) graphics card for increasing the intensity of the graphics of the simulations to the HMD (HTC Vive, China). Attached to the HMD were two 3D earpieces to produce distinct, full surround 3D sound. Two hand-held controllers were connected remotely to the computer to offer interactions with the virtual world and intuitive responses to participants. The physical area at the laboratory for the necessary movements while immersed measured 3m by 2.2m. Additionally, two base stations were positioned at the opposite vertices of the experiment area to track participants' movements and actions from the HMD headset and touch controllers. A flat-screen monitor was utilised to simultaneously monitor participants' activities in the virtual realm (pictured in Figure 5).

Figure 5. Features of the VR gadgets in use by a participant during a VR fire emergency evacuation and mitigation drill

3.7 Data collection and evaluation

The experiment success metrics were designed to be evaluated by the mean results of the participants of the research. Data were collected as a post-experience self-reflection in questionnaires administered to assess the specific objectives after each immersive experiment. As employed predominantly in the dissertation, self-assessment has been widely used in related literature to collect data for hazard-risk assessments and training successes. In this way, participants' propensity to inflate responses decreases if they become responsible for the evaluation (Ross et al., 1999). Following this approach, the respective studies for this dissertation included a Likert scales questionnaire immediately after the immersion. This was an attempt to understand participants' subjective perception of VR’s suitability for safety countermeasures (i.e., the hazard risk assessment for the safety of working in the factory simulation, the capability of the VR plant simulation for EPR, and whether they had gained the competencies required to evacuate if an emergency fire occurs while engaged in a related activity). To this end, participants evaluated their perception of the simulation model's suitability in fulfilling the central RO. However, the pre-movement time and evacuation time in publication 4 were measured while participants were immersed in the simulation. Memory tests were not administered in the studies for this dissertation since the skills gained were transient, as Bechtold et al. (2018) hint that such tests would require constant repetition and practice to internalise retention in the long-term memory. Publication 5 required both quantitative (i.e., questionnaire) and qualitative data in the form of suggestions and discussions for optimising the simulation for productivity and workplace safety.

3.8 Addressing the respective SQ for the dissertation

To address SQ1, SQ2 and SQ3 of Figure 1, which sought to investigate VR's utilization prospects in hazard risk assessments, fire evacuation drills, and EPR procedures, respectively, two 3D simulations were implemented in the study as previously explained. These were a LIB factory process (for the hazard risk assessment) and the GPP maintenance activity (for the emergency fire evacuation and mitigation drills).

3.8.1 VR hazard risk assessment in a manufacturing factory simulation

Publications 1 and 5 were designed to assess the possibility of effectively implementing the 3D factory simulation in the VR environment to improve working processes and safety compliance through the HIRA initiative. This was addressed firstly through WSC (publication 1) to ensure that the vital ingredients for implementation of HIRA (publication 5) in the factory simulation were possible before the subsequent assessment, evaluation, and control/mitigation of the factory. The factory simulation constituted the manufacturing environment and machinery dynamisms for participants to assess the hazards associated with the processes. This procedure addressed the effective implementation of VR for HIRA in the manufacturing facility according to the central RQ. A convergent parallel mixed method for data gathering after the immersive VR assessment in the LIB factory, as Figure 6 portrays. In publication 1, participants performed a single-subject designed research experiment that focused on understanding their perception of VR application for factory hazard risk assessment. Quantitative data in the WSC questionnaire were analysed to answer SQ1 partly. Following this analysis, qualitative data in the form of interviews were utilised to answer participants' perceptions of the dominant hazards identified in the factory. On the other hand, publication 5 incorporated quantitative data as a questionnaire for the JSHIRA procedure and qualitative data as discussions for optimizing the factory layout to answer SQ1 fully. By adopting an inductive approach, both studies began with data collection after the immersion and later proceeded to more general propositions based on the observations.

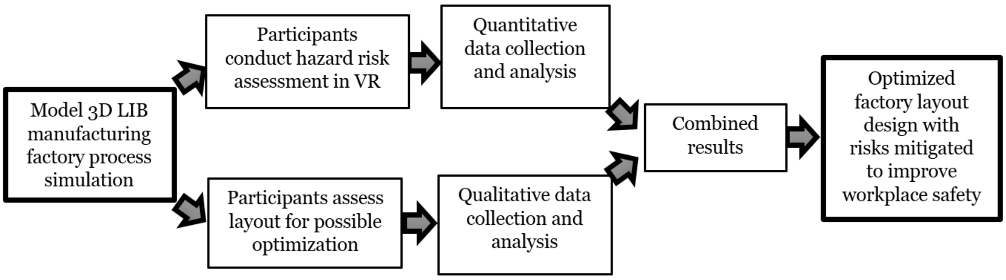

Figure 6. Convergent mixed method design for publications 1 and 5

Participants scored their perception of each identified hazard (i.e., likelihood and severity of an accident) on a Likert scale (5-point). Subsequently, the risk score was evaluated according to *Equation 1*, which correlates to the 5x5 risk matrix (Figure 7). Although the risk matrix has some limitations and, in some instances, is unreliable for the HIRA, it was readily applicable due to its ease of use, particularly for the novices who conducted the risk assessment. More comprehensive methods like FTA, FEMA or HAZOP assessments have higher successes, but with experienced safety personnel (Tian et al., 2015). In the analysis, the risk score categorization (Table 3) was rated according to the risk matrix. Therefore, the hazard with the lowest risk was rated 1, and catastrophic hazards were ranked at 25 according to Table 3 ratings to achieve the respective risk score. This scoring process was repeated after the risk mitigation (i.e., instituting corrective measures in the layout for eliminating or reducing the categorized risk to acceptable levels) to ensure that identified hazards were reduced to the negligible or marginal category in Figure 3 of publication 5.

Risk score = The probability (likelihood) of an accident ∗ severity (impact) *(1)*

The results of the 19 participants (publication 1) of the initial study (i.e., the WSC) indicated profound proximity of the simulation to the features (i.e., M = 4.16, SD = 0.59) and dynamisms (i.e., M = 4.21, SD = 0.69) of an actual factory. Similar results were equally obtained (i.e., M = 4.47, SD = 0.50) regarding the possibility of a hazard identification process by applying a fully immersive VR technology. Furthermore, the 32 hazards identified in the factory simulation by the 15 participants (publication 5) that was assessed and quantified into (negligible, low, and medium) at a paired sample t-test (i.e., M = 14.7, SD = 5) were controlled/mitigated to acceptable risk ratings. This intervention consequently resulted in a statistically significant difference (i.e., M = 7.8, SD = 3.6) at $t(31)$ = 6.79 and $p < .001$ at a confidence level of 95%, suggesting a reduction between the hazards in the initial factory simulation and after the JSHIRA procedure through the fully immersive VR procedure.

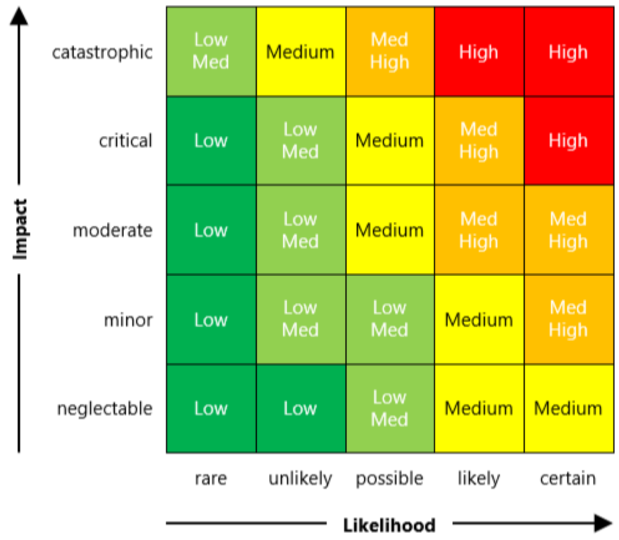

Figure 7. The 5X5 risk matrix *cited from* (Maziah Munirah et al., 2019)

Table 3. Risk score categorizations and mitigation requirements

Risk category		Risk score	Description (priority)	Action required
Severity	**Likelihood**			
Negligible	Rare	1 – 4	Very low	No action is required
Minor	Unlikely	5 – 8	Marginal	Caution notice
Moderate	Possible	9 – 14	Medium	Moderate impact
Critical	Likely	15 – 19	High	Major change needed
Catastrophic	Certain	20 – 25	Very high	Immediate correction

3.8.2 Evacuation and mitigation assessment during the plant maintenance activity

The evacuation possibility and durations from the GPP during the fire emergency were addressed in publications 2 and 4 in answer to SQ2. As explained earlier, these studies involved purely quantitative research methods for data collection through a questionnaire. Publication 2 was a within-subject design that sought to assess the suitability of employing a VR-SG for safety training by engaging the participants in the plant maintenance activity before the fire eruption that necessitated evacuation and mitigation. As a result, publication 4 in a between-subject design methodology was utilised to evaluate the effect of the activity on evacuation prospects by comparing the results of the experimental group (i.e., those tasked with the activity) to a controlled group (i.e., those without any responsibility in the simulation) before the fire broke out. Both participating groups were to evacuate the plant the moment they realized that there was a fire.

For the purposes of utilizing a deductive approach in both publications 2 and 4, a theory was selected and then tested with data.

In analysing the data, the pre-movement time and total evacuation durations for the groups in publication 4 were recorded for statistical comparison to assess participants' reaction to the fire hazard and subsequent egress duration from the plant. These measurements were taken for both groups with the independent sample *t*-test to evaluate if the maintenance activities adversely affected the safe egress time. This was followed by the assessment of the presence experience in the simulation. The WS presence questionnaire used in several VR simulation experiments (e.g., Kritikos et al., 2020; Schwind et al., 2019; Zou et al., 2017), was utilised to evaluate participants' sense of presence perception while immersed in the virtual realm. A 7-point Likert scale questionnaire was employed to measure the fidelity of the evacuation drill from the plant. These measurements aimed to understand how participants perceived the virtual simulation on fire safety to be realistic for fire evacuation drills. The study hypothesised that a maintenance activity in a plant simulation before a fire emergency adversely affects participants' pre-movement time during an emergency evacuation in VR. Furthermore, the second hypothesis postulated that an engaging maintenance exercise amid emergency fire evacuations increases the *sense of presence* in the VR simulation.

Results of the studies in publication 2 (i.e., from the 38 participants) indicated that the VR-SG training in the GPP simulation was realistic and close to an actual plant (a total of 87% in agreement). The study also demonstrated that learning in the simulation was effective by granting participants knowledge of safety procedures to answer the study's main research question. Regarding publication 4, a substantial mean difference of 20.84 seconds was recorded between the pre-evacuation duration of the two groups of participants. Furthermore, this difference at the pre-evacuation stage resulted in a further evacuation delay deference of 17.84 seconds between the group. Accordingly, a substantial statistical pre-evacuation time difference for the activity group (i.e., M = 60.12, SD = 23.94) and without the activity group (i.e., M = 39.58, SD = 21.39) caused the delay t (52) = 3.26, p = .002) at a 95% significance. These results affirm the hypothesis that a maintenance task in VR causes a substantial delay for these participants engaged in an activity by realizing the impending hazard late to initiate a quick evacuation response. Subsequent assessment of the groups' distraction and involvement factors according to the presence measurement in the VR simulation environment of publication 4 suggested that the maintenance activity added an extra sense of reality to the simulation to affirm the second hypothesis. Furthermore, a positive safety margin was obtained, which testified that the plant simulation was safe for occupancy and evacuation during the emergency fire in the VR environment.

3.8.2.1 Plant tenability criteria evaluation

To ensure that participants' evacuation durations in the simulation were realistic and safe for the design of the powerhouse, an assessment of the available safe egress time (ASET) according to the estimation for the duration of compromised tenability of occupants' egress during fires from a building as enshrined in the BS PD 7974-6:2019 standard (BSI, 2019). was evaluated for the factory model. Beyond this duration, the conditions in the building during a fire would become untenable for occupancy (Pauluhn, 2020). A comparison (safety margin) was made between the computed ASET and the required safe egress time (RSET) for occupants to evacuate according to Equation 2 successfully. For a building to be secure according to the performance-based fire safety engineering requirements, the time to egress from any part of the building when a fire occurs (i.e., ASET) needs to be more than the RSET (Manes & Rush, 2020).

$$\textit{Positive safety margin} = ASET > RSET \qquad (2)$$

The ASET was computed by the total of the detection time (*Tdet*), the premovement time (*Tpm*), and the travelling time (*Ttravel*) for the most remote evacuee of a building according to (Figure 1 of publication 4) and *Equation 3 below*.

$$ASET = Tdet + Tpm + Ttravel \qquad (3)$$

From this formula, the ASET value correspondingly amounted to (73.8+30+82.14), equaling 185.84 seconds. This value represents the available time for a single occupant to exit the building to the safe point (Fig. 4 of publication 4) in the event of a fire outbreak. The mean results of both groups (i.e., 82.42 for the activity group) and (1.e., 64.58 seconds for the group without the activity) were both shorter than the ASET (185.84 seconds). The implication was that, although the activity caused some significant delays, the findings in VR suggest that this delay did not jeopardize the preestablished tenability criteria of the egress route in the powerhouse simulation.

3.8.3 EPR in a VR plant simulation

Before a fire emergency incident, adequate preparations are necessary to ensure that the essential evacuation routes and possible mitigation measures are instituted with emergency drills. Publication 3 addressed SQ3 regarding the effectiveness of VR for EPR. As in publication 4, this study's methodology also followed a between-subjects design with the experimental and control participants separately exposed to specific factory conditions (Figure 10). The purpose was to analyse statistically if a significant difference existed between participants who had some working experience in engineering (i.e., the experimental group) and novices (i.e., the control group). This was to test the hypothesis that participants with ample work experience possess a better safety self-efficacy than novices. The study follows a deductive approach, which is appropriate for studies designed to verify general theoretical principles to confirm or reject a hypothesis. According to the conceptual model in Figure 1 of the publication, the study assessed participants' safety situational awareness (SA) and the possibility of evacuation during a fire (evacuation drills) to address VR's capability for EPR. Other issues discussed in the study were the safety of the VR environment for the experiment in terms of simulator sickness and the ergonomics of the VR gadgets.

Two workers from industrial companies accessed the simulation and provided feedback for improvement. The tutorials before immersing participants involved, the features of the HMD with the gesture controllers for navigation, the activity to be performed for the assessment, and essentially the personal emergency evacuation plan (PEEP) for successful evacuation. After the individual experiments, participants answered the questionnaire, which adapted portions of the Slater–Usoh–Steed Questionnaire (SUSQ) to analyse participants' safety SA. The SUSQ scale measures participants' perception, understanding, and physiological response to the presence in the GPP simulation environment (Slater et al., 2006).

Regarding the effectiveness of the VR simulation for EPR, Kirkpatrick's model designed for evaluating training successes (i.e., *Reaction, Learning, Behaviour*, and *Results*) was utilised for the assessment. The simulator sickness questionnaire assessed the safety and ergonomics of the VR gadgets and technology in the experiment, particularly any possibility of VR-induced symptoms and effects (VRISE) in the simulation (SSQ). The independent variable (the effect of engineering work experience on the considered dependent variables) was evaluated from the combined responses to the first three questions. After the individual immersion and interaction with the virtual objects, the next stage was collecting the data needed to address the research problem. The data were evaluated for integrity before statistical tests by conducting a reliability (Cronbach's alpha) analysis. Finally, data interpretation and discussions of the findings were established.

The overall results of both groups regarding the prospects of a fully immersive VR environment for EPR indicated that substantial levels of safety situational awareness were achievable (M = 4.248, SD = 0.354, df = 52) in the simulation. Further assessments imply that the immersive environment could also be safe for

EPR despite the inherent potential for cyber sicknesses. The GPP VR environment could be an effective fire evacuation drill and control tool. Subsequent comparison of the three factors under investigation for the group of 21 members with work experience (M = 4.240, SD = 0.457) demonstrated no statistically significant difference with the group of 33 members without work experience (M = 4.260, SD = 0.42) regarding the potentials of fully immersive VR simulations for EPR, $t(52)$ = 0.199, p = 0.843. This proximity in responses suggests that the technology is suitable for both participating groups.

4 A SUMMARY OF THE INCLUDED PUBLICATIONS

This chapter summarises the results and the findings of the five publications compiled for the dissertation. This effectively utilised 3D simulation in VR towards improving accident prevention in factory processes and maintenance activities. To satisfy this objective, the dissertation firstly assessed the possibility of conducting a WSC and safety training of a factory/plant simulation in VR (publications 1 and 2, respectively), followed by subsequent experiments in emergency response preparations and emergency fire evacuations (publications 3 and 4 respectively). Further studies with the HIRA procedure with hazard control/mitigations were conducted in publication 5.

In all the five studies that form this dissertation, the experiment procedure and requirements were explained individually to all the participants with pre-experiment immersive tutorials. A vital part of the tutorials was on handheld controls for navigation and interaction since most participants had never been immersed in a VR simulation.

Table 4. The key findings of each publication

Publication	Title	Key Findings
Publication 1	Optimising Occupational Safety through 3-D Simulation and Immersive Virtual Reality	The results of the work safety checklist suggested that several hazards inherent in the factory simulation model could be identified in VR. This initial investigation was necessary to set the foundation for answering the effectiveness of the VR-based simulation for the HIRA process.
Publication 2	Simulation-based Safety Training for Plant Maintenance in Virtual Reality	The building and machinery of a VR simulation environment can duplicate the maintenance activity of an actual plant for safety training. An experiential evacuation drill is feasible in VR. Utilising serious games in VR increases participants' interest in promoting cognitive learning for safety practices.
Publication 3	Simulation-based assessments of fire emergency preparedness and response in virtual reality	The results specify that the three components of EPR safety awareness, safety knowledge, and safety mitigation abilities can be conducted effectively in a real-time VR plant simulation environment to increase plant safety. The findings likewise suggest that the simulation environment can be safe for ERP.

Publication	Title	Key Findings
Publication 4	Effects of an engaging maintenance task on fire evacuation delays and presence in virtual reality	A demanding maintenance activity can decrease situational safety awareness in a VR simulation. This decrease causes delay during the pre-movement phase when evacuating and further transferred to the overall evacuation delay. Interactive and engaging activities in VR simulations increase the sense of presence, which is the most vital ingredient in immersive simulations.
Publication 5	Factory Layout Design and Optimization Focusing on Accident Prevention	Hazard identification and risk assessment procedures in a VR factory simulation can be conducted alongside process optimization to control and prevent hazards in the simulation while designing the factory.

4.1 The prospects of VR for hazard risk assessment

The first publication, "*Optimising Occupational Safety through 3-D Simulation and Immersive Virtual Reality*", sought to evaluate the effectiveness of a VR manufacturing factory process simulation for assessing risks at the factory conceptual stages (Figure 8). The study was conducted with a group of participants exposed to the same condition (within-subject design). The research followed a simulation-based experiment with a mixed-method design for data collection from the 19 participants who evaluated this objective. Participants were recruited from both industry and academia. The prerequisite was an occupational safety card for a year of minimum work experience (työturvallisuuskortti). The purpose of this criteria was to attract only those participants who had industrial work experience and could therefore evaluate the safety concerns and compare the VR simulation to the traditional safety training exposure and influence they previously had. In this way, they could also assess the similarities of the simulation to an actual factory and compare the experiment's effectiveness to conventional (Powerpoint and lectures) risk assessment methods. Following the VR factory walk for identifying possible hazards, participants answered the questionnaire and, afterwards, the individual interviews. After immersion, the risk assessment was organised with a WSC, which identifies the hazards present in a facility and serves as a tool for assessing an organisation's compliance with health and safety at work legislations. For example, the general safety of the work environment, the safety of machinery, the possibility of electrocution in the factory, the availability of first aid kits, fire safety, and safety signage are some of the factors evaluated through the WSC. The results suggested that the safety of a workplace could be vividly assessed in the factory simulation with suggestions for instituting corrections. Besides, participants indicated a preference for VR over traditional safety methods. Likewise, participants could pinpoint various hazards present in the factory as prevalent hazards during the post-immersive interviews.

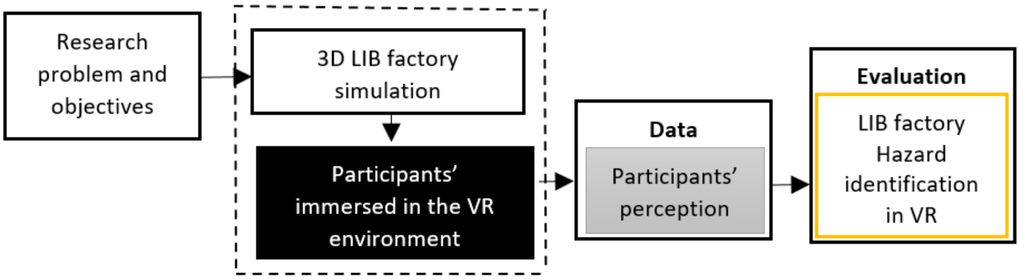

Figure 8. Conceptual study framework for publication 1

4.2 Evacuation training during plant maintenance in VR

The second publication, "*Simulation-based Safety Training for Plant Maintenance in Virtual Reality*" experiments with the suitability of a VR GPP simulation with a maintenance activity for evacuation drills and hazard mitigation. This is necessary as GPPs have peculiar operations and features that render the knowledge and training in safety practices from other industries inapplicable (Kwegyir-Afful et al., 2017). The study exposed participants to a 3D GPP simulation with a serious game (SG) design to evaluate these objectives. The SG constituted a cognitive activity for assessing learning capabilities during plant maintenance work. This was conducted using Hollnagel's cognitive reliability and human/machine interface ACM (Hollnagel, 1998). The target was:

- To investigate the prospects of a VR plant simulation for safety drills.
- To assess the effectiveness of learning through VR-SG modelling in the simulation set-up.

Study design: VR simulation, VR-SG. In total, 38 university students undertook the same activity during the immersive experiment (Within-subjects design) and provided feedback as the questionnaire. The criteria for the choice of participants were some industrial work experiences and the occupational safety card. The tutorial details included the safety procedures to replace the gas-powered engine air filter. The main instructions for performing the activity were also transcribed into text for the participants while conducting the study (Figure 2 of publication

2). The simulation environment consisted of three gas-powered engines in a hall measuring 35m by 50m. Participants were to replace the air filters of the engines (Figure 9); while working, a fire accident was designed to trigger, and participants were expected to stop working and evacuate. Another training requirement was to close the main gas valve outside that supplied fuel to the engines. Following the successful completion of the activity, participants responded to a Likert scale (5-point) questionnaire. The questions ranged from the realism of the training environment to an actual plant, the learning outcome, the ergonomics of the VR equipment, the suitability of the game-based VR training compared to traditional safety practices, and the knowledge acquired during the training. Figure 9 explains the study design.

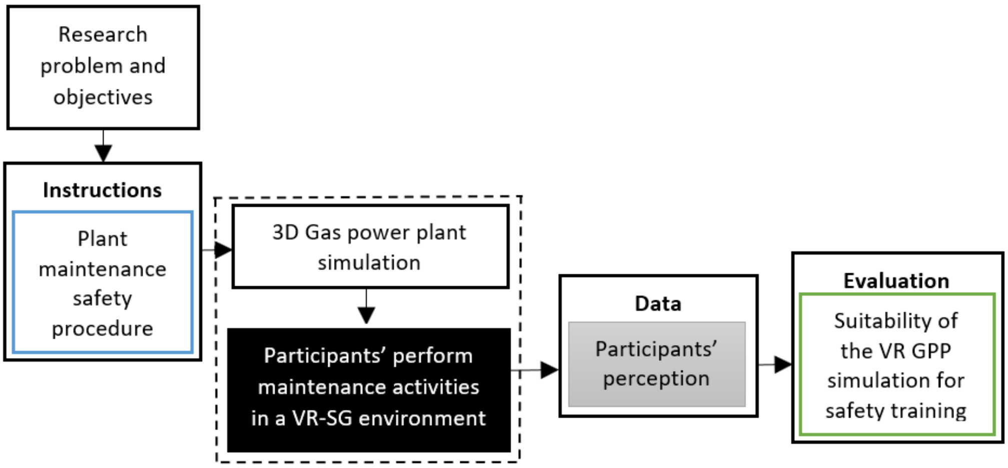

Figure 9. Study design for plant maintenance in VR

Most participants indicated that the plant simulation resembled an actual power plant. Similarly, the response to the knowledge that could be acquired in the simulation received appreciable results. The overall responses indicated that the gamified plant simulation and the VR environment could be utilised effectively (successfully) for training in safe work procedures and evacuations. In this study, the effectiveness of VR in contributing to safety training in the plant simulation was assessed by participants' responses regarding the success of the VR intervention, as explained in section 3.8.

4.3 Emergency preparedness and response in VR

In publication 3, titled:" *Simulation-based assessments of fire emergency preparedness and response in virtual reality*", this study sought to investigate the prospects of conducting an EPR procedure in a GPP VR simulation environment.

The EPR was presented and evaluated to test participants' situational safety awareness, safety evacuation knowledge and response, and risk mitigation skills during a fire emergency in the VR simulation. Furthermore, the safety and the ergonomic viability of the VR instruments and environment were assessed during the safety countermeasure. According to previous work experience in engineering, two groups of participants were involved in the exercise. The purpose was to experiment with the general notion that people with some engineering work experience had better safety situational awareness than novices. Bhide's (2017) VR fire emergency evacuation framework and Dhalmahapatra et al.'s (2020) VR-ACM were employed for the experiment with 54 university student participants. Figure 10 demonstrates the experimental between-subjects study framework. Four research questions were formulated according to the conceptual study design (Figure 1 of publication 3). These questions ranged.

I. The attainable levels of safety SA in the VR simulation were assessed by the Slater–Usoh–Steed Questionnaire (SUSQ) (Slater et al. 2006).
II. A measure of the effectiveness of the VR simulation exercise for FED and mitigation was investigated with Kirkpatrick's three-stage model for training evaluation.
III. To assess the safety and possibility of VRISE during the immersion. This was implemented with Rzezniczek et al. (2020) SSQ.
IV. To assess the similarities between the participating work experience groups regarding I, II and III results.

From the combined results regarding the safety SA (I) in the immersive environment (Table 3 of the publication), both participating groups scored high on a 5-point Likert scale, representing significant comprehension of their ability to visualise occurrences for initiating prompt evacuation responses. Similarly, positive results for (II) according to Kirkpatrick's training and learning evaluation methods were obtained concerning FED and mitigation exercises, including participants' acquired knowledge, interest, and skills. Also, the results for (III) showed negligible levels of cybersickness (VRISE) during and immediately after the simulation exercise, according to Table 5 of the publication, and most of the participants regarded the plant simulation as conducive and without the tendency of work-related musculoskeletal disorders (MSDs). However, no statistically significant disparity was realised between the two groups from the independent-sample *t*-tests of (I), (II) and (III) to answer (IV) in the affirmative, suggesting that both groups perceived the simulation as equally viable for EPR. This similarity indicated that the VR simulation model is suitable for experienced workers and novices in the three components of EPR tested. These were fire evacuation drills (FED), safety SA, and the immersive environment's safety and ergonomics (SE).

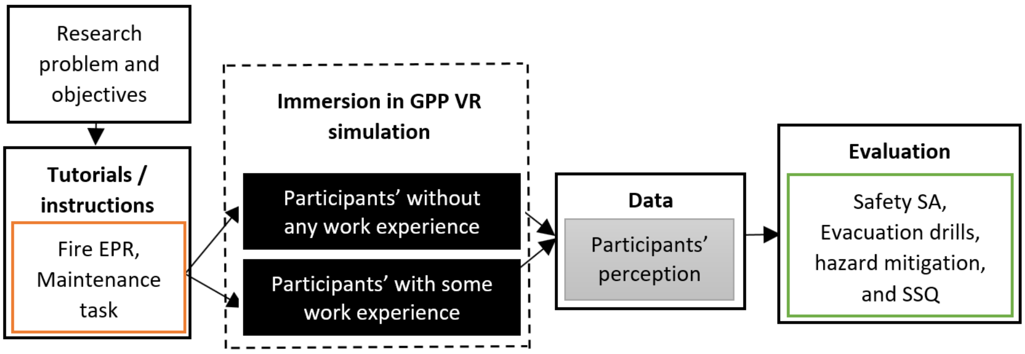

Figure 10. The conceptual study model of the EPR assessment in VR

4.4 Evacuation delays due to plant activity engagement and the sense of presence in VR

The fourth publication, "*Effects of an engaging maintenance task on fire evacuation delays and presence in virtual reality*", sought to evaluate the capability of occupants in a VR powerhouse simulation engaged with maintenance activity to recognise a fire emergency and initiate evacuations before the exit routes became untenable from the fire effluents. From a research ethical perspective, it is morally unacceptable to subject humans to actual fire emergencies to estimate the duration where the exit routes become untenable (TENK, 2019). Consequently, occupants' pre-movement time and evacuation durations during fire emergencies in buildings have not been experimentally validated (Manes & Rush, 2020; Pauluhn, 2020). For this reason, the study aimed to investigate the effects of engaging in maintenance activity on occupants of a 3D powerhouse simulation to sense a fire and evacuate to safety. subsequently, the levels of presence that participants experienced in the simulation due to the maintenance activities were evaluated to meet this aim. Through this process, the study contributes to sharing light on the need to embrace industrial VR applications for emergency egress tenability drills in the selected high-risk occupational setting – A gas power plant.

As in publication 3, publication 4 also followed a between-subjects design and with a deductive research approach. The training, therefore, consisted of evacuation drills in the current model (Figure 2 of the publication). Participants of the two groups immersed individually in the plant simulation constituted: the experimental (n=26) and the control (n=26), totalling 52 university student participants. The experimental group were tasked to replace the air filter of the third gas-powered engine, while the control group was not issued any activity. According to the emergency evacuation plan, both participating groups were informed to stop every activity and leave the building immediately upon seeing the fire. The visible smoke constituted the fire effluents, i.e. (toxic gases, smoke, carbon monoxide (CO) concentration and heat) were all presented as particles of visible smoke. Accordingly, the pre-movement time and the entire evacuation durations were measured and compared from the time the fire accident simulator triggered until each participant successfully evacuated. Subsequently, participants' subconscious levels in the virtual realm were measured on a 7-point Likert scale to assess which of the five factors of the present measurement was affected. The presence scale ascertains the level at which the simulation becomes the dominant reality (amnestic re-embodiment) with the Witmer–Singer (WS) presence questionnaire (Witmer & Singer, 1998). Figure 11 demonstrates the experiment procedure beginning with the tutorials, VR immersion, data collection, and evaluation.

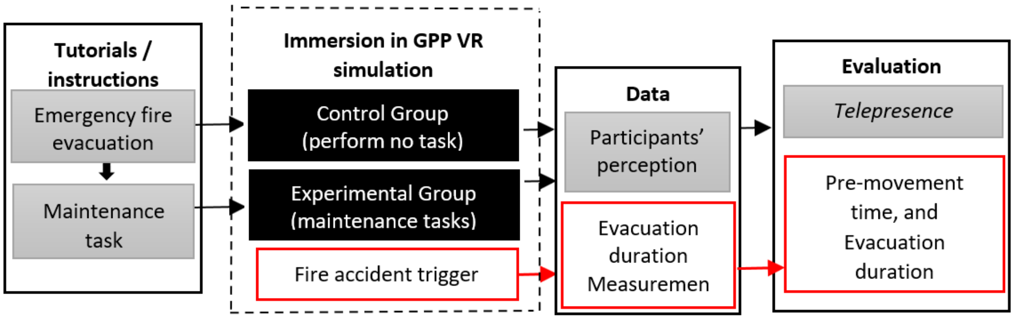

Figure 11. Experiment procedure for fire evacuation delays in VR

4.5 Accident prevention during the factory layout design

The fifth publication is titled "*Factory Layout Design and Optimisation Focusing on Accident Prevention*". This study aimed to design and improve the layout and safety measures in the LIB manufacturing factory model employed in publication 1. Figure 12 demonstrates the conceptual study framework. Manufacturing production processes usually undergo several layout modifications when production commences optimising productivity. Although such improvements are essential, they do not always incorporate the recommended safety risk assessments, rendering such changes hazardous. With the aid of the VC manufacturing simulation software, the factory layout comprising the building, machinery and manufacturing processes in 3D was modelled to meet the production requirements. All the necessary information regarding the procedures, equipment, and schedules for manufacturing LIBs were obtained from the research works of Heimes et al. (2018), Jinasena et al. (2021) and Lu et al. (2021).

Two groups of participants experienced the factory simulation to provide feedback for improving the layout and the risk assessment. The first group comprised eight stakeholders from the project company and Vaasa University. After detailed scrutinisation in VR, these stakeholders provided comments for rectifying the factory process layout for the required optimisation. The inefficiencies identified included excessive waiting times, too long travelling times, and gaps in scheduling.

For the hazard risk assessment, 15 student participants conducted the JSHIRA procedure after the immersive encounter with the manufacturing processes according to the activities at each production stage. They suggested rectifications to eliminate or reduce the identified hazards. This was in the form of a risk score (from 1 to 25) obtained from the severity (intensity) of the specific risk occurring and the likelihood (probability) of occurrence (Rout & Sikdar, 2017). Rectification measures were instituted into the factory model and re-visualized by the participants to provide improved scores (Table 3 of publication 5). By walking through the stages of production in the factory simulation, potential hazards were identified and categorised through the risk score. Some of the threats identified ranged from corrosive material falls, fire hazards, cuts, crash possibilities with robots, and forklift accidents. Following this categorisation, mitigation measures were instituted to address the identified threats, particularly those with a high-risk score, according to the JSHIRA. These mitigation measures ensured that the final factory design was safe from inherent hazards to the best of the knowledge of participants and authors of the study. In total, thirteen risks in the critically high-risk range in the study were noted and rectified. For example, a potential hazard like a crash with the robotic arm (Figure 13) was ranked critical on this scale. In addressing this hazard, machine guards were provided (Figure 14). Other mitigation measures to curtail threats included providing adequate machine fail-safe devices, slip-resistant floors, and radiation shields. Despite these measures, some hazards like forklift crush during loading and offloading at the storage section could not be reduced further. For this reason, training for forklift operators was recommended.

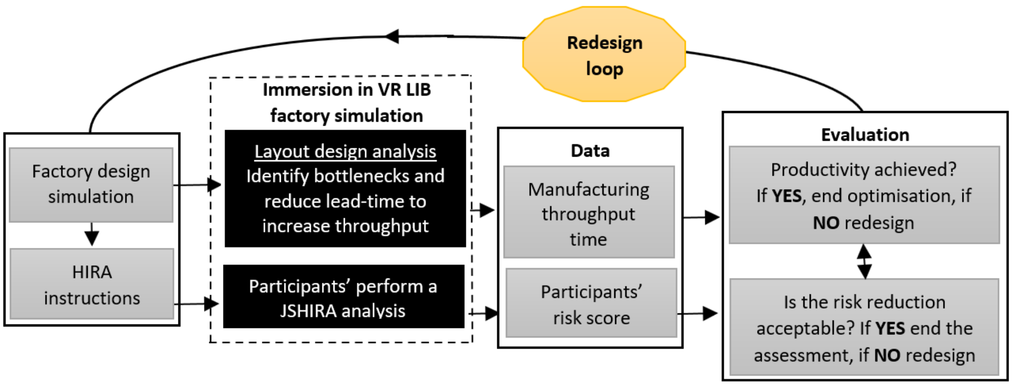

Figure 12. Conceptual framework of the layout design

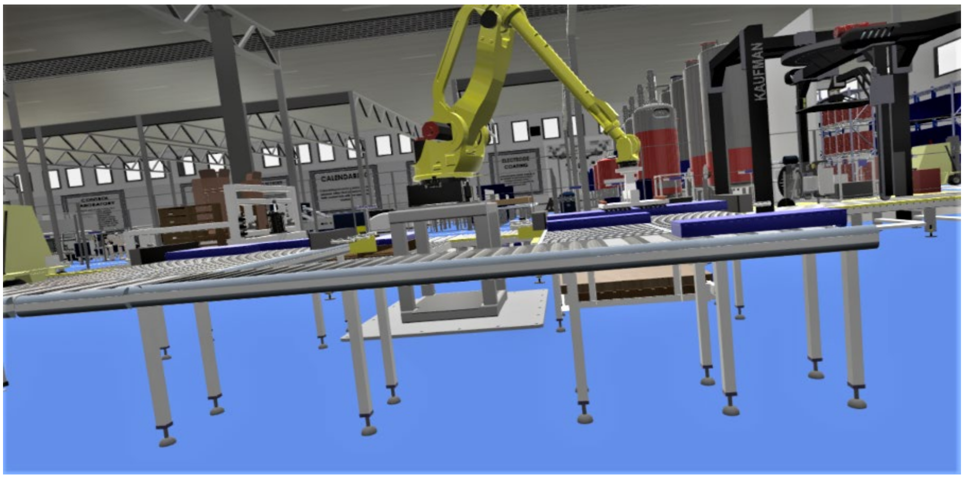

Figure 13. Hazard of the robotic arm showing access and exposure to the hazard

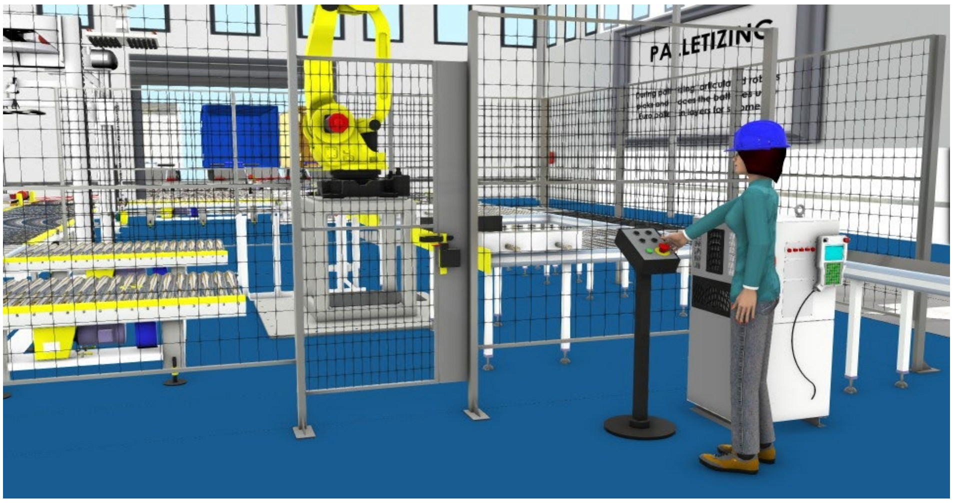

Figure 14. Prevention of a hazardous situation at the robotic arm (with safety guards to prevent access and exposure to the hazard)

5 DISCUSSIONS

The primary objective of this dissertation was to experiment and highlight the effectiveness VR plays in promoting industrial safety by preventing accidents. This chapter, therefore, presents the discussions, implications, and future works from the findings of each publication included in the study. Accordingly, accident preventive measures have been experimented with VR by conducting hazard risk assessments, emergency fire evacuation drills, and fire EPR activities in two digital factory models. These were explored in response to the main research question seeking to experiment with the factors that ensure the effective utilization of VR for accident prevention during emergencies while working in a factory and plant simulation. The countermeasures regarding hazard risk assessments involved a WSC evaluation (publication 1) with a JSHIRA procedure (publication 5), both in a 3D LIB manufacturing factory simulation.

Furthermore, the plant maintenance model was employed for fire EPR activities (publication 3), which constituted safety SA, and FED (publication 4) for accident prevention. The theoretical contributions of the dissertation are explored according to the RQs answered mainly by participants' perceptions of the preventive measures of the accident phenomenon. The managerial implications are also offered for implementing the actual results in the manufacturing and maintenance environment, processes, and activities. In this way, the dissertation advances VR utilisation in industrial safety countermeasures in workplaces that lack experimentations with VR simulation on accident prevention. Finally, the limitations with future research avenues are explained.

Regarding the validity and reliability of the quantitative part of the study findings, firstly, the content validity was ensured by covering the essential aspects of preventing accidents in the three safety countermeasures tackled for this research. According to the ISO 45001:2018 Health and safety management standard, these countermeasures were the HIRA (i.e., Clause 6.1.2: Hazard identification and assessment of risks and opportunities), emergency fire evacuation drills (i.e., Clause 7.2: Safety training to maintain competence), and EPR (i.e., Clause 8.2: Emergency Preparedness and Response) (ISO 45001:2018). Secondly, the results of the individual publications exhibited a strong correlation between the participant's scores for the suitability of the VR environment and the related safety countermeasure (e.g., Table 2, publication 1), indicating high construct validity. Thirdly, the logical (face) validity was also evaluated by the telepresence measurement (e.g., Schwind et al., 2019), which was scored high (Table 3, publication 4). Fourthly, the results of the study measures correspond to the findings of other empirical VR measures, suggesting that the studies possess high criterion validity. However, the ecological validity of the research could not be ascertained since experimenting with the VR accident scenario in a real-world setting could be catastrophic. VR fire simulations share this ecological validity issue (Bourhim & Cherkaoui, 2020). Regarding the reliability of the study, firstly, based on Cronbach's alpha measurement for internal consistency (reliability) of the test items was high (e.g., publication 3, $\alpha = 0.725$, and publication 4, $\alpha = 0.716$) to satisfy the construct reliability.

5.1 Theoretical contributions

This dissertation attempts to address multiple gaps in the literature on utilising static and dynamic ACM for accident prevention. For example, Tian et al. (2015) used the dynamic simulation-based quantitative HAZOP to display the propagation effects of an automatic process for risk assessment in a chemical process. Similarly, Baek & Heo (2021) demonstrated the realistic features of the dynamic FTA compared to the static fault-tree risk assessment methods for an electric power system. Despite these benefits of the dynamic ACMs, they, however, fail to capture the real-time information for analysis at the accident scene. Besides, these models cannot provide the immersive environment for interacting with virtual objects, processes and activities as 3D modelling and simulation in VR do (Dhalmahapatra et al., 2020). Therefore, the theoretical lens of this study is the successful representation of accident causation factors and scenarios for accident prevention in manufacturing processes and plant activities. The salient theory employed in this model is Heinrichs' domino ACM, which emphasises that accidents are avoided by removing the dominos. These dominos are explained as unsafe acts, unsuitable conditions, lack of requisite training, and management oversight that causes accidents. Hence, this study adds to the theoretical development by integrating VR technology with accident causation theories to present realistic accident scenarios for safety training, identifying inherent hazards for assessing risks at the workplace, and EPR applications. These safety countermeasures were experimented with during a factory process simulation while participants were engaged in work activities. The following responses are highlighted to address each research sub-questions about the identified gaps.

5.1.1 Response to research sub-question 1

Referring to the first research sub-questions, SQ1: "What is the effectiveness of employing a VR emergency scenario for hazard risk assessment and mitigation in a manufacturing factory process simulation?" the participants of the study assessed this effectiveness in publication 1 by the level of realism experienced in the simulation, the proximity of the simulation to actual processes, and the capability of analysing the production safety. Additionally, the success of conducting HIRA by the participants and implementing control/mitigation measures through the VR technology in publication 5 is a measure of the effectiveness of the technology in answering SQ1. The results obtained from publications 1 (i.e., the WSC, Table 1) and publication 5 (i.e., the JSHIRA, Table 3) of the manufacturing factory simulation indicated that the VR simulation environment possesses several features and processes close to the natural, rendering it suitable for conducting an occupational hazard risk assessment procedure. Besides, participants' results suggested a preference for VR simulations in identifying hazards while designing and optimising a factory layout process than conventional practices. Overall, the most prevalent accident risks identified were cut injuries from the slitting machine, crashes with the calendaring machine and falls, among the most probable accidents in manufacturing cycles (Hovden et al., 2010).

Interestingly, VR research in other engineering fields, such as construction engineering (e.g., Seo et al., 2021), mining engineering, and aviation (e.i., Chittaro et al., 2018), found similar results when identifying hazards and assessing risks in their related simulations. Secondly, the results are consistent with findings in the discipline; for example, Or et al. (2009) emphasised that fully immersive VR technology can generate an interactive environment for a user immersed in the virtual world when working close to industrial robots. A view held by some VR simulation studies (e.g., Bordegoni et al., 2022; McGovern et al., 2020) indicates that the training environment in a VR simulation provides a motivating, encompassing, and the novel realm of a simulated model for skills enhancement. These findings suggest that VR training models incorporating 3D simulations can offer a close to a natural environment, manufacturing processes and active work interactivity, thereby providing immense visibility, high interest, and learning capabilities as a measure of its effectiveness for accident prevention. As in most immersive VR applications for accident prevention, the current study equally focused on the subject matter by separating participants from the external world to minimise the cognitive load. Furthermore, the simulation of realistic accident scenarios in the VR environment contributes to research by allowing participants to experience situations that are impossible to present in traditional safety training sections. For example, life-threatening fires, dangerous industrial practices and processes, or exposure to hazardous and harmful conditions.

Figure 15. The JSHIRA procedure

5.1.2 Response to research sub-question 2

Referring to SQ2, "How effective can a gamified virtual activity be implemented in a plant simulation with work activities for safety training?" the results of publications 2 and 4 were designed to address this question. The level of effectiveness was first measured by how well participants perceived the simulation with the gamified activities to be engaging, fascinating and interactive enough for a real-time emergency safety training section (publication 2). Secondly, it was evaluated in publication 4 by how well participants could sense the danger and evacuate safely when the fire emergency ensued while performing the work activities. Essentially, the substantial delay in evacuation duration from the pre-movement phase during the plant fire emergency indicated a lack of awareness of other occurrences during the crisis. Secondly, the experiment contributes to research evaluating the sense of presence in VR applications by allowing participants to experience hazardous scenarios and content for the required reaction rather than merely observing accident phenomena, thereby supporting experiential learning. Accordingly, a subsequent increase in the sense of presence measurement of the experimental group, who performed the activity, indicated an extra sense of involvement and interactivity in the plant simulation. These results of the significant increase in the sense of presence due to the task performance coupled with the safety training intervention in the VR simulation explain effective accident prevention countermeasure in answer to SQ2.

5.1.3 The tenability of the exit routes during the evacuation

According to the performance-based fire safety engineering design principles, the evaluated ASET needs to be more than the RSET to yield a safety margin for a building to be safe. These values were considered to ensure that the plant simulation for the evacuation drills was assessed for the safety of occupants during emergency fires. From *Equation* 3, the ASET of the plant building was evaluated from the *Tdet*, *Tpm* and *Ttravel*. This was compared to the RSET recorded from the simulation results to obtain the tenability of the exit routes during evacuation (margin of safety) of both experimenting groups. The travelling time was measured from the length and breadth of the plant to be 50 meters and 35 meters, respectively (*Figure 4* of publication 4). Therefore:

The *Ltravel* = 50 + 35 = 85 sec.

and, *Ttravel* = 85/1.4 = 60.71 sec. (travelling time)

According to a GridFlow evacuation experiment, the *Tpm* for the average occupant of a building under fire is about 30 seconds (Bensilum & Purser, 2003). For the *Tdet*, although some researchers argue that occupants of a building react stochastically during fires, Sarwar's data for a facility having a floor area of (50*35) meters using a multi-fire effluent detector yields 73.8 seconds (Sarwar et al., 2018). This value considers the tenability criteria for visibility, temperature extremes and carbon dioxide (CO_2) concentration with other asphyxiants during enclosed fires (Qi-quan & Xiang-dou, 2017). Therefore, from Equation 3, the ASET of the building according to the performance-based fire evacuation limits is:

$$ASET = 73.8 + 30 + 60.71 = 164.51 \text{ sec.}$$

The RSET value was the average egress duration when participants evacuated from the plant during the fire. From publication 4, the experimental group obtained a mean evacuation duration of 82.42 seconds, while the control group measured 64.58 seconds. A positive margin of safety was achieved for both groups to satisfy *Equation 2* since the ASET was more than the RSET under both experimental conditions (i.e., experimental and control), according to Table 5 below. This indicates that the plant building was safe enough for realistic evacuation drills. These results also signify that although the maintenance activity caused a significant delay, participants could notice the fire and evacuate before the exit routes turned untenable from the effluents of the fire. Thus, the realistic emergency scenario and response activities in the findings further buttress the effectiveness of the VR simulation for safety training.

Table 5. The tenability of the exit routes during the evacuation

Evacuation durations	Experimental group (*n* = 26)	Control group (*n* = 26)	Δ (Sec)	% Δ
	M	*M*		
ASET	164.51	164.51		
RSET	82.42	64.58	17.84	24.27
Safety margin	81.42	99.93	18.51	20.41

5.1.4 Response to research sub-question 3

In SQ3, “What is the effectiveness of utilising VR for EPR in the plant simulation while conducting a maintenance activity?” To answer this question, we investigated situational safety awareness, FED, and mitigation, as well as the safety and ergonomics of the virtual realm. Applying these safety countermeasures in the fully immersive VR simulation measured the effectiveness of answering SQ3. The collated results from the participants in Table 3 of the publication demonstrate high levels of situational awareness were achieved, which affirm the hypothesis that significant levels of situational safety awareness are attainable in a VR plant simulation. Similarly, a positive trend was established while investigating the prospects of the plant VR simulation for FED and fire mitigations according to Kirkpatrick’s evaluation model; therefore, the suggestion is that the VR environment provides an effective platform for EPR activities in the plant simulation. These findings also agree with the works of researchers like Slater et al. (2006), Lee Chang et al. (2017), and Giglioli et al. (2019). They also assessed the situational safety awareness of their VR environments with the SUSQ during training and established compelling evidence to suggest the potential of VR in this venture. Likewise, the works of Kinateder et al. (2014) and Vasudevan & Son (2011), who evaluated the effectiveness of simulation-based exercises for FED in VR, likewise attest to this in the affirmative.

Regarding the safety and ergonomic viability in terms of VRISE possibility in the plant environment, the obtained SSQ results in Table 5 of publication 3 affirmed the third hypothesis of the study that a VR simulation could be safe with negligible SS effects provided the required safety measures are established. This was because the instituted measures, as well as the clarity of the HMD headset, minimised any possibility of VRISE. The measures instituted to achieve these positive results included:

- The minimum age of 18 years for participants aimed at preventing seizures.
- A virtual translucent wall in the immersive environment to provide a visual boundary for preventing crashing or falling, and

- A maximum of 25 minutes per immersion, according to the HTC Vive safety guide. Patel & Dennick (2017) safety and regulatory guidance for using the HMD headset highlight these measures. In the same way, participants' response to the ease of navigation and controls while immersed with the subsequent feeling during and after the exposure suggests comfortability in terms of the VR set-up and device ergonomics during the exercise.

Thus, the findings indicated that participants in an immersive virtual simulation can experience situations close to real-life and that specific industrial hazardous scenarios can be presented for critical assessments necessary for EPR actions. However, no statistically significant differences were found in all the three factors being; situational safety awareness, FED and mitigation, and safety and ergonomics (Table 6 of publication 3) to support the hypothesis that participants with some engineering working experience perceive the VR simulation environment more effective for EPR than novices. The similarities in the results of the two groups nonetheless demonstrated that VR for EPR is not exclusively suitable for those with some engineering work experience but is also ideal for both groups. The findings also contribute to recent studies like Dado et al. (2018) and Sekaran et al. (2021), who implemented the digital factory concept for accident prevention.

5.2 Results synthesis

Firstly, several hazards inherent in the factory layout design has been identified for the necessary risk assessment and possible mitigation (Publication 1). Secondly, the study has demonstrated that participants in a GPP VR gamified simulation environment can realistically experience fire emergencies to react, which is necessary for evacuation training. Additionally, interactive maintenance activities in fully immersive VR simulations increase participants' attention and sense of presence in the virtual realm (Publications 2 and 4). Therefore, the substantial levels obtained in the studies answer SQ2 about how effective a gamified VR activity could be instituted in a plant simulation for safety training. Thirdly, the results have shown that it is vital to exercise proactive safety situational awareness and vigilance while working on demanding plant maintenance activities, according to the principles of EPR (Publication 3). Fourthly, further assessment of the safety of the maintenance activity in a plant simulation suggests that any delay at the pre-movement phase due to the lack of situational safety awareness was transferred to the total evacuation duration, emphasising the importance of early recognition of an emergency for safe evacuation when fire threatens a building (Publication 4). Finally, inherent hazards and production delays in a manufacturing layout design can be rectified in VR to ensure a safe working environment and increased productivity (Publication 5). Thus, signifying the effectiveness of the immersive VR simulation for HIRA.

Overall, the VR accident prevention intervention procedure followed a path of modelling in 3D, scrutinising details in VR, and safety training or instituting rectifications after the risk assessment according to the VR-ACM. This allowed participants to experience realistic hazardous situations while engaged in industrial activities in a safe virtual environment, which is impractical in real life. Consistent with Nedel et al.'s (2016) research, the immersive VR simulation provides the most effective means of analysing the dynamic performance of a production sequence to reduce workplace accidents. These findings are synthesized to form the dissertation framework in Figure 16.

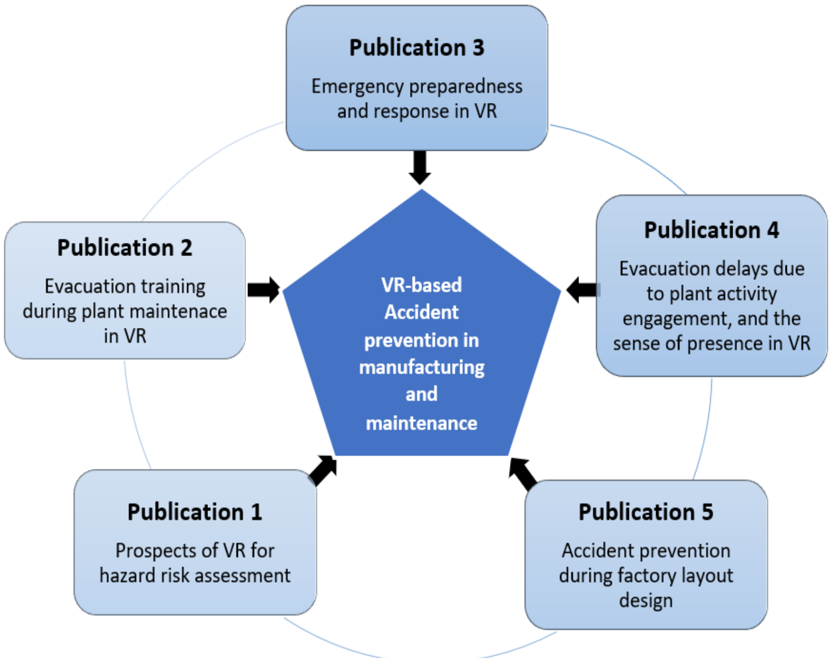

Figure 16. Synthesized research model

In the LIB manufacturing simulation, the study has integrated the factory process with accident preventive measures in a JSHIRA process to mitigate hazards and ensure workplace safety in a digital factory. The JSHIRA procedure follows the sequence in Figure 15. The optimisation constituted line balancing and removing inefficiencies and bottlenecks by reducing lead-time to increase the production throughput. An essential aspect of the optimisation involved equipment repositioning and shortening conveyor lines to minimise the production time while ensuring worker safety. A substantial throughput increase of 4.51% was achieved through this process, which is deemed necessary to ensure the sustainability of the design for safety processes. Although the study concentrated on hazard risk assessments for accident prevention in LIB manufacturing and plant maintenance with emergency evacuation activities, the generic framework and procedures for the simulation and hazard risk inspections can apply to a broad range of factory and plant processes for safety improvement. Similarly, the study of the maintenance activity in the GPP simulation before the emergency fire outbreak indicated that although some delays were observed in both the pre-movement time and evacuation time, all the participants were able to evacuate the plant building before the ASET, which indicates that substantial levels of situational safety awareness were possible in the immersive environment. Alternatively, the sense of presence measurement in the plant stated that those who partook in the maintenance activity before evacuation showed a higher level of presence in the simulation environment. These plant simulation features and results suggest that the VR environment is suitable and adequate for fire EPR.

5.3 Overall contributions

First, to the author's knowledge, no previous research in peer-reviewed databases has experimented with the effects of engaging in maintenance activity on situational safety awareness and evacuation durations during an emergency scenario in VR. In addressing this literature gap, the study conducted experiments to evaluate participants' reactions during the simulated emergency.

Second, the study extends the limited research of VR applications for safety improvement in a factory manufacturing process and plant maintenance activity by conducting hazard risk assessments to evaluate the technology's applicability. Therefore, this study is one of the first to consider utilising occupational activity-based simulations in a fully immersive VR factory/plant processes and activities to assess the environment's suitability for safety training, hazard risk assessments and EPR.

Third, the dissertation complements the limitations of existing VR studies for safety countermeasures in manufacturing, which concentrates mainly on the efficacy of the VR technology in comparison to traditional safety measures and therefore fails to expand applications for work practices in the industry.

Fourth, the study adds a voice to emergency fire evacuation delays during industrial maintenance activities and provides avenues for further improvement. Although the literature on VR utilisation in accident prevention is relatively new, it has flourished rapidly in recent years with significant empirical considerations on learning and training. For example, Leder et al.'s (2019) research compare VR with PowerPoint for safety training, Lovreglio et al. (2021) simulation training in using fire extinguishers, and Joshi et al. (2021) VR safety training study in the concrete industry. This dissertation also contributes to the safety of factory manufacturing processes and the safety of plant maintenance activities in VR.

Fifth, the study findings contribute to the literature by emphasising the benefits of VR for hazard risk assessments in a manufacturing factory simulation during the design and optimisation of the production processes. In addition, the investigation expands on the effects of activity performance in increasing the sense of presence in VR simulations, which is the primary purpose of fully immersive applications. Consequently, these contributions echo the work of Feng et al. (2018), Giglioli et al. (2019), and Torda et al. (2020), explicitly highlighting the technological and training capabilities of the unique versatility of VR simulations in occupational safety countermeasures.

Sixth, the main features in the manufacturing processes of a conceptual factory have been simulated in 3D and visualised in VR for better comprehension by identifying inherent hazards for the necessary rectification with throughput optimisation. From the findings of the individual studies, this dissertation is expected to contribute to the broader industrial safety engineering field to encourage engagement in more realistic VR studies on workplace fire evacuation successes during emergencies and generally in hazard risk assessments and emergency preparedness.

5.4 Managerial implications

Factories and plants establish several accident preventive measures in their safety management policies to ensure adequate safety. These measures include adherence to relevant safety training (Kazar & Comu, 2021) sections, hazard risk assessments (Aven & Flage, 2017) and emergency preparedness and response (Karkoszka, 2020). . These are implemented according to statutory regulations and standards such as the ISO 45001:2018. Therefore, this dissertation intended to contribute to these safety countermeasures by experimenting with accidental emergency plant situations in a VR simulation for the respective safety countermeasures as stated in the objectives of this dissertation. Implications are that VR factory and plant simulations can be utilised for training and emergency preparedness through hazard risk assessments in factories and plants as occurs in other industries such as construction, mining and aviation.

The findings suggest that VR in fire emergencies provide participants with captivating scenarios of the simulated work environment with interactions for experiencing real-time fire emergencies in a safe and risk-free environment. Essentially, the study demonstrates that some lessons relevant to emergency fire preparedness can be acquired in a completely virtual environment of a conceptual factory simulation. Likewise, a virtual environment can reveal details of an abstract plant facility incorporating the essential features and occupational activities for EPR. Furthermore, the experiments showed that VR simulations are suitable for training experienced workers and novices in safety countermeasures. Other implications suggest that safety situational awareness drills are essential for prompt evacuation in the case of a fire emergency in a high-risk working environment such as a GPP.

5.5 Limitations and Future research directions

Firstly, the main limitation encountered in the study was that the risk assessment was not conducted by SHE experts but primarily by students and factory staff who evaluated the risks as workers in the factory. For this reason, some critical hazards were likely overlooked. Secondly, the employed VR technology included the regular HMD headset having audio-visual sensations with haptic feedback for interactions, but without multisensory features like thermal and olfactory senses. For this reason, the fire hazard in the simulation was represented by only visual particles without smell or heat sensors. A multisensory interface with thermal and olfactory senses could be viable in future VR simulation research for more holistic sensory representations. Thirdly, the speed of movements in the plant was sometimes superficial, as participants could hurdle over structures during the evacuation in a manner not realistic. However, such limitations are not exclusive to this experiment, as it is shared in several VR ecological validity issues. Besides, Bourhim & Cherkaoui (2020) and Castro-Mondragon et al. (2022) indicate that technology advancements intend to cover this gap by narrowing the differences between virtual and real-life interactions. Fourthly, the employed VR set-up could accommodate only one participant at a time, and therefore, the study neither considered the effects of evacuation congestions nor crowded evacuation situations. In the future, there is the possibility to include multiple users in the same VR model to experience the issues of numerous evacuees intuitively.

Additionally, since participants' presence data were recorded after the investigation, it could be subject to the retention of the individual participants. For this reason, the results could be affected based on participants' memory capabilities. Therefore, questionnaires in further VR for accident prevention could be presented to participants while immersed in the simulation.

Despite the limitations mentioned above, the dissertation demonstrates important salient implications from the findings of the individual studies, which contribute to industrial accident prevention and will spur further VR research in factory and plant fire emergencies.

6 CONCLUSIONS

This dissertation tackles three salient areas for accident prevention in manufacturing processes and plant activities to prevent industrial accidents. The two models utilized for the experiment were a LIB manufacturing factory simulation and a GPP maintenance activity. The countermeasures investigated got accident prevention are HIRA, safety training, and EPR. These were experimented with by immersing participants in a fully immersive VR simulation environment to intuitively experience the accident phenomenon for the safety intervention. The dominant theories employed for the two simulations used for the study were the VR-ACM which employs the systems theory of accident causation, and the emergency fire evacuation training model. These were implemented in the five publications to address the three SQs intended for the study. The factory simulation constituted the building, equipment dynamism and manufacturing processes for the HIRA with the WSC and the JSHIRA procedure. On the hand, the safety training and EPR involved plant activities on a gas-powered engine in a serious-games study design before a fire hazard that necessitated evacuations and subsequent control/mitigation in the factory design.

Indeed, the results from the publications demonstrate the success of the fully immersive VR simulation for accident prevention in the selected industries, processes and activities. This was evident from several hazards identified and assessed for the required risk reduction, control, and mitigation in the initial design of the manufacturing process simulations. Additionally, the results of the emergency evacuation drills and the EPR exercises in the plant simulation environment while conducting maintenance activities attest to the potential of the technology for safety training. Moreover, the safety assessment of the VR set-up (i.e., effects of VRISE, the usability of the HMD, and handheld controllers with gesture sensors) of the immersive virtual simulation environment indicated that the setup was reasonably safe and ergonomically viable for the accident prevention assessment.

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Optimizing Occupational Safety through 3-D Simulation and Immersive Virtual Reality

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Abstract. This paper evaluates the effectiveness of computer simulation and the immersive virtual reality (IVR) technology for occupational risk assessment improvement. It achieves this by conducting a risk assessment on a 3-D simulation of a Lithium-Ion battery (LIB) manufacturing factory. This is necessary since calls for the enhancement of occupational risk assessments continue to dominate safety improvement measures in manufacturing context. Meanwhile, industries such as aviation, mining and healthcare employ advanced versions of IVR for risks awareness with successes. However, applications for safety in manufacturing context is only at the infancy although it utilizes IVR profitably for product and production optimization issues. The study involved 19 participants who performed the assessment with the aid of a safety checklist followed by open-ended semi-structured questions and interviews. Results indicates an outstanding utilization capability of IVR for risk assessment. Furthermore, the assessment pinpoints specific safety issues in the factory that requires attention and improvement.

Keywords: Risk assessment · Hazard identification · 3-D simulation · Immersive Visual Reality · Manufacturing industry.

1 Introduction

This study integrates the potentials of the Immersive Virtual Reality (IVR) technology for enhancing occupational safety through a 3-D simulation of a lithium-Ion battery (LIB) factory. Specifically, the study aims to evaluate the extent that this technology can be employed to conduct an effective industrial risk assessment procedure that is key to occupational health and safety of manufacturing factories [1]. The Occupational Health and Safety Assessment Series standard (OHSAS 18001:2007) defines risk as the combination of the probability of occurrences and results of a predetermined hazardous event [2]. Risk assessment is therefore defined in the document as the process of calculating risk magnitude and deciding if the risk is tolerable. Besides, evidence indicates that safety measures are best implemented during the planning stages of a facility. Moreover, traditional means of analyzing risks at the planning stages is handicapped due to its inability to envisage details of production processes adequately [3,4]. Implications are that, the safety of detailed manufacturing processes cannot be critically assessed until after construction and production. For this reason, the IVR technology which has the capability to simulate manufacturing equipment, the environment, robotic manipulations, products and production processes in real-time is currently gaining industrial acceptance [4,5].

Although this technology was initially developed for computer games, today it has evolved as a viable industrial tool in example; engineering, construction, telecommunications, military and healthcare to optimize operations, product design and processes. Moreover, it is employed for safety improvements in some instances [5]. Generally, industrial applications of the technology for safety proves that IVR is the best currently known method for safety training, hazard identification and accident reconstruction [6].

However, there is scanty evidence to support its successes in manufacturing for safety improvement despite these impressive strides in provided by the virtual technology. For example, in a 154-article review relevant to Virtual Environment (VE) applications in manufacturing from 1992 to 2014, only 4 addressed applications of the technology for human factors [7]. One touched on workers safety training [8], another on safe working environment for the disabled [9] and two on simulations of human models for risk assessments [10]. Furthermore, future research directions of some of these applications seek to apply the technology pragmatically for safety analysis in emerging manufacturing fields. For these reasons, this paper formulates the following research questions:
RQ1: Is it possible to conduct a risk assessment in a 3-D model of a manufacturing factory?
RQ2: How close is a 3-D simulation to a factory in terms of layout, equipment and manufacturing procedures?

RQ3: What extent can IVR identify hazards and risks of a 3-D simulation in manufacturing context?
RQ4: Does a 3-D simulation of a manufacturing edifice and analysis through IVR provide better means of evaluation compared to traditional means of risk assessments at the planning stages?

Hence this paper is structured as follows to address these questions; in the next section, the methodology describes the structure, data and empirical framework of the research follows. Subsequently, literature based on applications of this technology for occupational safety optimization in manufacturing is reviewed to provide a theoretical background. Thereafter, presentation of results follows which elaborates and discusses the research findings. Finally, the study concludes in retrospect with the limitations and suggestions for further research.

2 Methodology

Figure 1 describes the design of the research which starts with the afore mentioned problem statement about the need to strengthen occupational risk assessments in manufacturing through simulation and IVR.

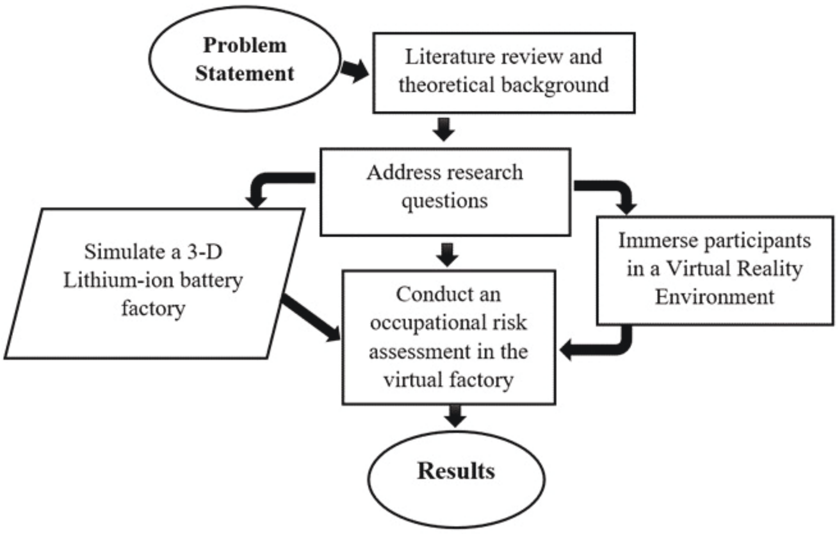

Fig.1. The design of the research

The research follows both qualitative and quantitative research methods that includes experiments and surveys with yes or no answers. Three open-ended questions proceed this to complement the data. None of the participants had any adverse issues with an IVE nor mental disability. The mean age of participants was 34 (SD = 8.1) and had

8.5 (SD = 6.2) years of work experience. 47.4% of the respondents were from industry and manufacturing while others were from research and education institutions. The purpose and procedure of the research, particularly the experiment was first explained to participants individually. Afterwards, the researchers provided detailed tutorials for the navigation and control of the LIB virtual factory through utilization of the stereoscopic HMD device. Emphasis on the safe use of the system such as the proper adjustment of the head set for clarity and visibility follows. Subsequently, the researchers' highlighted the safety zone for the immersion. Thereafter, the signing of the informed consent form by both the researcher and each participant follows. After a thorough walk and inspection of the facility, example (Figure 3), participants then completed the risk assessment form. This constituted 35 questions according to the workplace safety checklists (WSC) which conforms to the occupational safety and health (OSH) answer fact sheet. The safety checklist covers a broad range of health and safety issues that includes the factory environment, availability of First Aid kits, presence of safety signs and fixed guards for articulated robots and running machinery. Other issues are storage for chemicals and explosive materials, fire protection, warning systems and the possibility of electrocution. The first part of data gathered constitutes a quantitative analysis for the risk assessment based on disagree or agree questions and thematic categorization for the open-ended questions.

The Visual Components (VC) simulation software was used to build the 3-D virtual factory. This enables scrutiny of all processes for the manufacture of the 2170 LIB cell. The simulation processes consist of the raw material offloading stages through anode and cathode mixing, coating, calendaring and slitting. Others are cell winding, electrolyte filling, and cell welding. The formation cycling and packing into modules follows. Finally, the palletizing and shipment stages completes the simulation.

3 Theoretical Background

Several industrial applications of IVR simulations for safety exists. These are; training of employees in a simulation through IVR for safe operation [11,12], Likewise, in risk assessments associated to human responses in emergency situations [13]. Furthermore, safety levels have been improved through the application of a Plant Simulator (PS) that constitutes process simulation and accident simulation for normal as well as abnormal accident scenarios [7,14]. Moreover, the simulation-based training (SBT) software enhances human-robot collaboration (HRC) safety training. Meanwhile, virtual prototypes are also suitable for human factors and ergonomics at factory design stages [15]. Thus, through the application of 3-D simulation and scrutiny with IVR, a rise of safety levels in some high-risk sectors such as in the construction industry has become possible [16]. Similarly, the mining industry records successes for safety improvement [17,]. Theoretically, applications of the technology for risk assessment involves (a) analyzing and evaluating the risks associated to a specific hazard: Termed risk analysis and/or risk evaluation. (b) Determining the most appropriate methods to eliminate the identified hazards and (c), controlling the risks when the hazard posed is impossible to eliminate. Termed: risk control. Accordingly, this research utilizes this sequence while participants experience immersion in the 3-D virtual factory.

3.1 Occupational Risk Assessment

The primary and key technique to achieve optimum workplace safety is an active and vibrant occupational risk assessment (ORA) procedure [18]. In manufacturing cycles, hazard-based qualitative risk assessment with risk management implies locating and identifying jobs, operations and procedures that have the tendency to increase the likelihood of exposure to injury, damage or even fatalities [19]. OHS management system therefore clarifies risk according to time horizons and severity such as imminent and serious risks to prioritize and structure control and intervention mechanisms. A workplace survey is vital in achieving a serene occupational safety environment. This implies identifying and assessing all health and accident risks at the workplace with suggestions for improvement. The design of this paper hopes to achieve that. Section 5 on Act 701/2006 of the Finnish Occupational Safety and Health Enforcement and Cooperation Act for Workplaces emphasizes and enforces requirement for frequent and efficient inspections to uphold safety standards [20].

3.2 Technology and Simulated Environment

According to Wang et al., [21], there are four independent definitions of the reality-virtuality (RV) simulation technology. These are augmented reality (AR), augmented virtuality (AV) pure real presence, and pure virtual presence (VR). Currently, the pure virtual presence termed Virtual Reality has gained industrial attention and acceptance [22]. Primarily, this is because in the immersion, VR possesses better visibility, accessibility and much more capable for analyzing complete virtual environments. In addition, it generates complete virtual images with the head mounted display (HMD), sensory handheld controllers and base stations. A Virtual reality environment is a 3-D real time graphical environment that makes it possible to visualize and interact with simulated models in a virtual environment [15]. One is immersed (termed immersive VR) in the environment when using the technology to interact with seemingly real or physical situations. The purpose of the application of IVR technology is to transfer the user of the headset from the current natural location to the simulation in the virtual realm. This makes it possible for critical scrutiny of the factory for hazards at the planning stages.

In order to run the 3-D simulation and immersion needed in the virtual realm, a Windows 10 computer with the following specifications and accessories was utilized: An Intel core i7 processor having a speed of 3.6 GHz Dual-Core and a random-access memory (RAM) of 32GB. Importantly, it is installed with an NVIDIA GPU (GTX 1070 GeForce gaming graphics card. For the immersion, an HTC VIVE equipment incorporating a head-mounted display (HMD) coupled to hand-held controllers connects to advanced gesture controls for navigation. Two base stations track movements to produce the virtual environment of the 3-D simulated models. Figure 3 shows a participant immersed in the virtual environment of the LIB manufacturing factory.

3.3 Lithium Ion Battery (LIB) Manufacturing Factory

The choice of a Lithium Ion Battery (LIB) manufacturing factory for this simulation is due to growing concerns of global warming and the current interests and growth for green energy. The facility incorporates advanced automation, robotics and state-of-the-art technology (Figure 2) to produce the LIB that powers electric vehicles (EV).

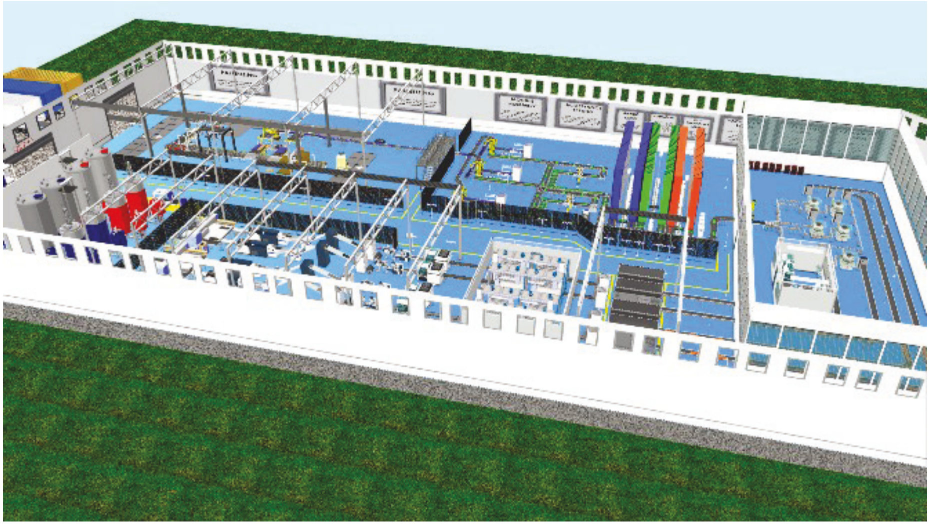

Fig. 2. The 3-D model of the utilized LIB factory

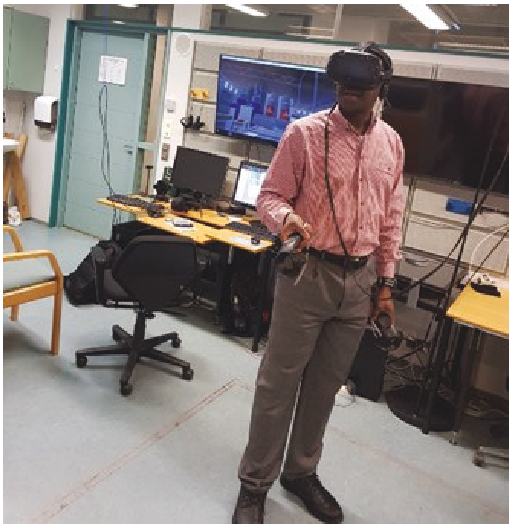

Fig. 3. Risk assessment of the 3-D LIB factory through IVR.

4 Results and Discussions

Table 1 presents results of the risk assessment that answers RQ1 which seeks to investigate the possibility of conducting a risk assessment in a 3-D simulation through IVR. While answering the question in relation to statement A in Table 2 about the possibility of conducting risk assessments in the simulation, 52.63% of participants agreed and 47.37% strongly agreed. Accordingly, the mean value of 4.47 (SD = 0.50) for the statement A (Table 3) indicates proximity of respondent's perception. Furthermore, the answers obtained for statement C also in Table 2 of the capability of IVR in analyzing the safety of production attests to RQ1 in the affirmative.

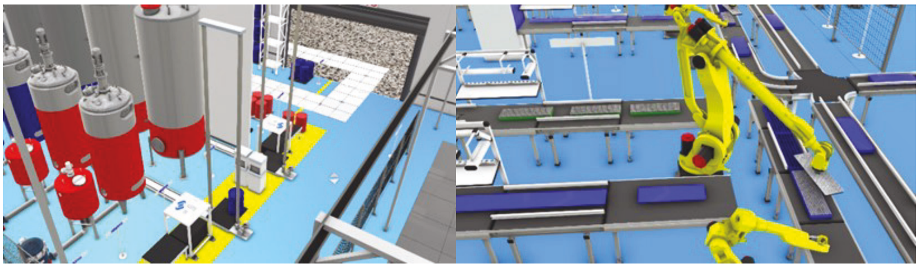

Fig. 4. Inside view of the factory showing mixer tanks and articulated robots at work

Table 1. Combined risk assessment results

Risk assessment results (in percentages)		YES	NO	No answers
1	Are floor surfaces free of water, oil or other fluids?	95	5	0
2	Are passageways clearly marked?	68	32	0
3	Are walkways/doorways clear of boxes, cords and litter?	68	32	0
4	Are stairways clear of boxes, equipment and other obstructions?	95	5	0
5	Are stairs and handrails in good condition?	100	0	0
6	Will personnel be working above where others may pass?	63	37	0
7	Will personnel be working below others?	53	47	0
8	Are covers/guardrails in place around pits, tanks and ditches?	95	5	0
9	Is the level of light adequate for safe and comfortable of work?	100	0	0
10	Are work items that are regularly used within easy reach?	89	11	0
11	Is there sufficient access to machines/equipment?	100	0	0
12	Are appropriate manual handling aids readily available?	74	21	5
13	Are all machine parts adequately guarded?	74	16	11
14	Are warnings appropriate for any hazardous areas?	68	32	0

15	Are all hazardous products stored appropriately?	74	21	5
16	Is stored material stable and secure?	84	11	5
17	Are items placed neatly and securely on shelves?	79	21	0
18	Can items on high shelves be easily reached?	79	16	5
19	Are the elevated platforms properly and handrails secured?	89	11	0
20	Are switchboards in a safe operating condition and secured?	89	11	0
21	Are machine guards in place on all operating equipment?	84	16	0
22	Are emergency stop buttons clearly visible and operational?	53	47	0
23	Are chemical and hazardous substances stored safely?	89	5	5
24	Are hazardous products stored away from heat sources?	74	21	5
25	Is there a possibility of electrocution?	26	74	0
26	Is there adequate ventilation or an exhaust system?	84	16	0
27	Is ventilation equipment working effectively?	79	21	0
28	Are First Aid Kits easily accessible and prominent areas?	84	16	0
29	Is the location of the First Aid Kit clearly identified?	74	26	0
30	Are exits and exit routes equipped with emergency lighting?	79	21	0
31	Are exits and exit routes accessible?	84	16	0
32	Are there signs and arrows indicating the direction to exits?	68	32	0
33	Are locations of fire alarms/firefighting clearly identified?	89	11	0
34	Are extinguishers properly mounted and easily accessible?	84	16	0
35	Are there enough extinguishers present?	58	37	5

Concerning the simulation's proximity to a real factory (statement D in Table 2), 63.16% agreed while 26.32% strongly agreed and 10.54% neither agreed nor disagreed. Similarly, 63.16% agreed while 31.58% strongly agreed and 5.26% disagreed to the proximity of the simulation to actual manufacturing processes (statement E in Table 2). The mean value for the statement D is 4.16 (SD = 0.59) and for the statement E it is 4.12 (SD = 0.69). These responses complement RQ2 that indeed, the simulation is quite close to a real factory.

Table 2. Results of IVR's suitability for risk assessment of the 3-D simulation

Perceptions of 3-D simulation and IVR for risk assessment (in percentages)	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

A. Possibility to conduct a risk assessment	0	0	0	52.63	47.37
B. Ergonomics of the HMD	0	0	21.05	21.05	36.84
C. Capability to analyse production safety	0	0	0	63.16	31.58
D. Proximity to a real factory	0	0	10.54	63.16	26.32
E. Proximity to actual processes	0	5.26	0	63.16	31.58
F. Preference to IVR than traditional methods	0	5.26	10.54	42.10	42.10

Although much of the response showed a high level of correlation, there were however some questions that had YES and NO spit answers. For example, in question 22, that asks about the visibility and operational performance of emergency stop buttons. The split was because some participants concentrated on a YES answer for the visibility while others chose a NO answer based of its operation. Actually, there were emergency stop buttons, but they were not operational in the simulation. Hence, the split answers.

While analyzing the extent to which the IVR can identify hazards and risk factors present in the plan as RQ3 asks, statement C in Table 2 provides 63.16% in agreement and 31.58% strongly in agreement to the capability of IVR to analyze safety of production in the real factory. Secondly, the mean value of 4.21 (SD = 0.69) obtained from question F of Table 2 shows that IVR is more suitable for risk assessment than traditional means of assessment. Consequently, results from Table 2 and Table 3 shows that IVR is truly a more appropriate and effective means of assessing risks at the planning stages compared to traditional methods such as text and 2-D plan and answers the RQ4.

Table 3. Results of IVR's suitability for risk assessment of the 3-D simulation

Questions related to the simulation and IVR walk (Strongly disagree= 1, disagree=2, neither /nor agree=3, agree = 4, strongly agree= 5)	Mean	Standard deviation
A. It is possible to conduct a risk assessment in a 3-D simulated factory	4.47	0.50
B. Ergonomics of the HMD for the assessment	4.16	0.74
C. Capability to analyse production safety	4.21	0.69
D. Proximity of the simulation to a real factory	4.16	0.59
E. Proximity of the simulation to actual manufacturing processes	4.21	0.69
F. Preference to IVR for risk assessment than traditional methods	4.21	0.83

During the risk assessment, participants identified diverse hazards present in the factory that requires attention. Two mentioned the potential for falling as the main hazard while four indicated gas leakage and another four participants also observed that the presents of fast-moving robots and machinery were the main hazards present in the simulation. Besides, there were nine hazardous issues that were reported only once. (identified as other in Figure 5a).

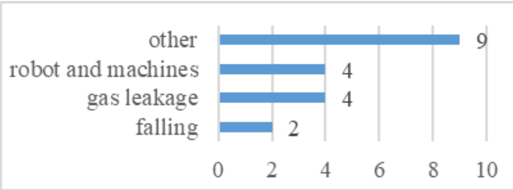

Fig. 5a. Hazards identified in the LIB factory

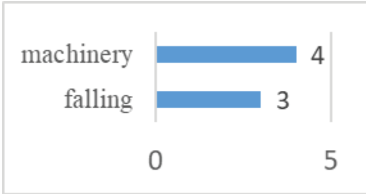

Fig. 5b. Probable accidents

However, the most probable accidents identified in the simulation were related to machinery and falling (Figure 5b) which are actually prevalent amongst the high causes of accidents in the industry [23].

5 Conclusions

This paper has employed an IVR technology for occupational risk assessment to a 3-D model of a LIB manufacturing factory. The risk assessment constituted the 35 WSC questions administered by 19 participants individually while immersed in the virtual realm. Overall, results of the research indicate that IVR is highly capable to improve work place safety through a more active occupational risk assessment that constitutes hazard identification and a safety walk of the facility even in the plan. Furthermore, the assessment provided ample suggestions for instituting and implementing the necessary control measures. Generally, participants overwhelmingly indicated preference to IVR risk assessment of the factory at the planning stages to traditional methods of risk assessment. The exercise has demonstrated abundantly that indeed, a full-scale occupational risk assessment procedure can occur in a 3-D simulation of a manufacturing factory with the aid of an IVR technology. Despite these results, the research encountered a few limitations necessary for recognition. Firstly, the exercise concentrated exclusively on VR and the simulation was equally limited to LIB production. Therefore, in the future, the researchers intend conducting the simulation and IVR in other manufacturing factories to compare and validate the results presented in this paper. Likewise, we hope to involve the safety, health and environment (SHE) managers within the sector for the risk assessment. Secondly, the overall simulation process froze repeatedly due to simultaneous multiple simulations of the production process. As such, the exercise sometimes took more time than initially anticipated although most participants enjoyed the walk and scrutiny in the virtual realm. While

IVR's utilization for safety in manufacturing context is only at the initial stages, this paper demonstrates both empirically and pragmatically its utilization potentials in manufacturing to fill this research gap.

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Simulation-based Safety Training for Plant Maintenance in Virtual Reality

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This paper presents a 3-D simulation model for safety training in an interactive and fully immersive virtual environment (IVE). The training comprises application of serious games (SGs) designed for filter replacements on a gas-powered plant (GPP) engine model by participants based on plant maintenance health and safety environment (HSE) regulations. Although maintenance work on GPP constitutes significantly in the share of hazards in the industry, there is however, scanty research related to simulation-based training for safety. Research nonetheless indicates the success of this technology in other industrial fields. For this reason, this study explored the possibility for training in safe work practices during maintenance in a gamified virtual environment. The Unreal real-time 3D game engine software was employed for creating virtual objects in the simulation. In total, 38 participants individually undertook the training in the virtual realm and provided feedback on a 5-point Likert scale. Questions pursuant to the assessment included the efficacy of acquired safety knowledge and skills, proximity of the simulation-based training to reality, and the interests and preference of SGs-IVE towards safety training. Results demonstrates participant's perception of the prospects and learning outcome of SGs-IVE towards safety training: A factor that promotes greater cognitive learning for mindful safety practices.

Keywords: Serious games · 3-D simulation · Immersive Virtual Environments · Safety training · Safety countermeasures

1 Introduction

The operation and maintenance of power plants are inherently dangerous. Research also indicates that 88% of accidents are due to dangerous practices on the part of individual workers [1]. Some of these dangerous practices occurs during maintenance work. For this reason, realistic and vibrant safety trainings are not only relevant but necessary in ensuring the prevention of accidents and unwanted occurrences [2]. An interactive and immersive virtual environment (IVE) has the potential in simulating imaginary or real situations for training in a safe computerized environment [3].

In recent times, there has been increase in applications of immersive virtual environment based serious games (SGs-IVE) for industrial training. These training sections provide realistic, safe and interesting tasks for learning that are not obtainable otherwise [4&5]. This is due to the gamified and engaging benefit of the combined technology that promotes greater cognitive learning [3&6]. According to pedagogical research, learning in such an environment presents authentic means of knowledge acquisition [4]. Another reason is that the current generation experiences digital environments in computing technologies and devices and are more conversant in their uses. Thus, learning becomes natural when implemented as games [3&7].

High-risk organizations such as mining, construction and nuclear power plants employ simulation-based safety-training models successfully for risk awareness and safety training [5,6&7]. Despite these outcomes, there is little utilization for industrial safety training in some other risky occupational practices [8&9]. Due to the peculiarity of hazards associated to the operations of gas-powered plant (GPP), successes of the effectiveness of SGs-IVE for safety training in some industries does not necessarily guarantee its effectiveness in GPPs. For this reason, the current study constructed a 3-D virtual model of a GPP to experiment the suitability of the technology for safety training. Specifically, the framework integrates SGs-IVE to provide a pedagogical and behavioral experience. The training lasted from August 2018 to October 2019 for safety training in air filter replacements.

This paper therefore seeks answers to the following research questions.
RQ_1: How close to reality can a 3-D GPP simulation be for safety training?
Since simulation-based training sections varies due to the employed software, technology and design, it is necessary to verify whether our training model is realistic and suitable for the purpose.
RQ_2: How effective will learning in SGs-IVE gas-powered plant be?
Answers to this question will determine the success or otherwise of the experiment.
RQ_3: How suitable is the SGs-IVE equipment for safety training in terms of equipment user-friendliness? In order to determine the benefit and preference of the training section, there is the need to experiment whether the equipment and technology employed performed favorably during the training as well as participants' preference for SGs-IVE.

The paper is structured follows to address these questions: The next section describes the background, methodology and empirical framework of the research. Subsequently, explanation of the experiment procedure follows. Thereafter, the results and discussions elaborate the findings. Finally, the study concludes in retrospect with implications of the findings, limitations and suggestions for further research.

2 Background and Framework

Advances in computer technology has improved productivity and profitability for several industrial applications [7&9]. Such technologies can be channeled to boost productivity and prevent unwanted occurrences and accidents during maintenance work [1](9). SGs, virtual reality (VR) and 3D process simulations are among state-of-the-art technologies employed in industry for this purpose [10].

Figure 1 represents the experiment model and procedure that begins with a review of publications related to applications of SGs-IVE for safety training. Our previously described three RQs were expanded to 6 questionnaires for participants. The researchers explained the experiment procedure to all participants and after agreeing, signed the informed consent form. In consistent with health and safety environment (HSE) regulations, participants were informed beforehand to identify, and control hazards and risks present at the workplace. Participants were then immersed individually in the 3-D simulation with the aid of a head mounted display (HMD) and hand held controllers as seen in Figure 3.

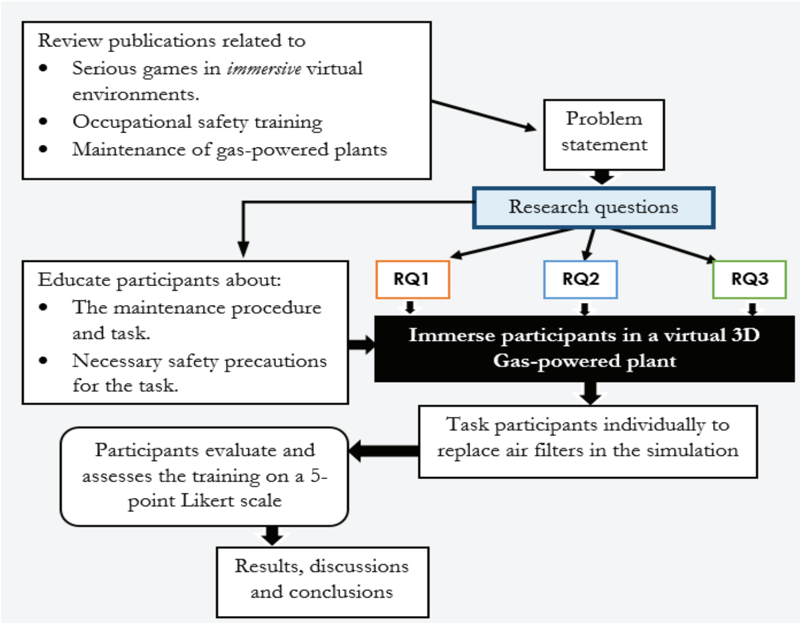

Fig. 1. The experiment conceptual model

Criteria for the choice of participants was a basic level of safety training and industrial work experience. Most students and workers contacted already had this safety card as well as industrial exposure as summer workers and were thus suitable for the experiment. Another criterion was that each participant needed to be conversant with the English language in order to understand the survey instructions and to answer the questionnaire correctly. After performing the task for the training in the virtual realm, participants then answered the 6 questions framed on a 5-point Likert scale from strongly disagree to strongly agree. The combined results of these assessments are synthesized in response to the 3 research questions in Figures 5, 6 and 7.

2.1 Experiment procedure

The entire training for each participant lasted about an hour. The exercises were performed with the aid of on-screen instructions as in Figure 2. Figure 3 shows a participant under training. Details of the task included removing the filter cover, installing new filters and replacing the filter cover after the exercise.

Fig. 2. Task completion

Fig. 3. A participant under training

3 Results

Figure 4 presents the combined response of participants to the six questions in the questionnaire numbered A to F.

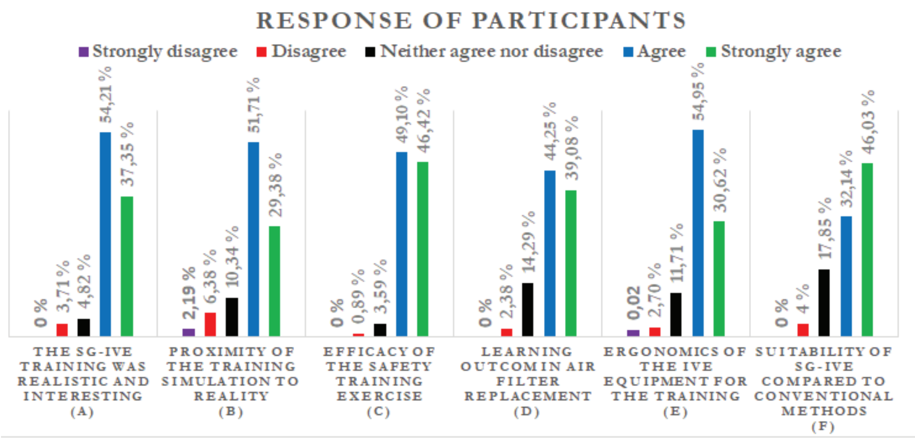

Fig. 4. Coordinated response of participants to the questionnaire

3.1 Mapping answers to research questions

Coordinated results of all participants were synchronized to answer the initial research questions. The first research question **RQ1** regarding the proximity of the safety training in the simulation to reality, responses **A** and **B** in figure 4 were mapped to RQ1 and Figure 5 presents the result.
A. The SGs-IVE training was realistic and interesting.
B. The simulation of the power plant engine / environment was close to a real plant.

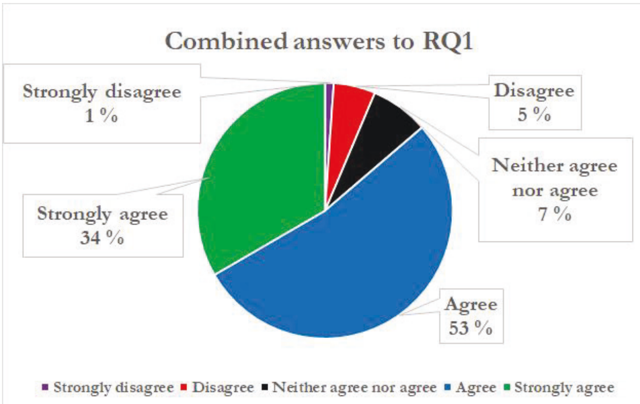

Fig. 5. Combined answers to the first research question (RQ1)

The second research question RQ2 regarding the effectiveness of learning, questionnaires **C** and **D** in Figure 4 covered RQ2. Figure 6 presents the specific result.
C. The SGs-IVE technology offered me an effective way of learning to work safely.
D. The training has granted me knowledge of safety procedures in GPP maintenance.

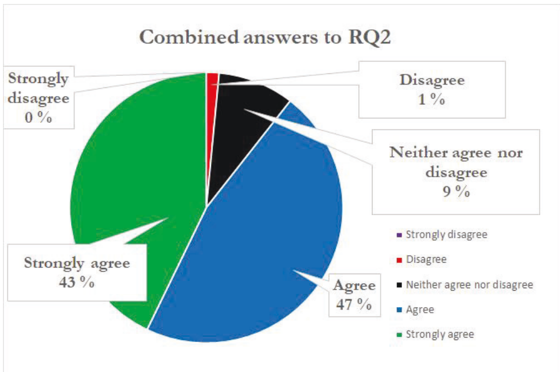

Fig. 6. Combined answers to the second research question (RQ2)

In answer to the third research question RQ3 pertaining to the user-friendliness and suitability of equipment for safety training, response to questionnaires **E** and **F** in Figure 4 were mapped to RQ3 and Figure 7 presents the result.
E. The training equipment and technology were suitable for the training.
F. SG-IVEs are more suitable for training compared to conventional methods.

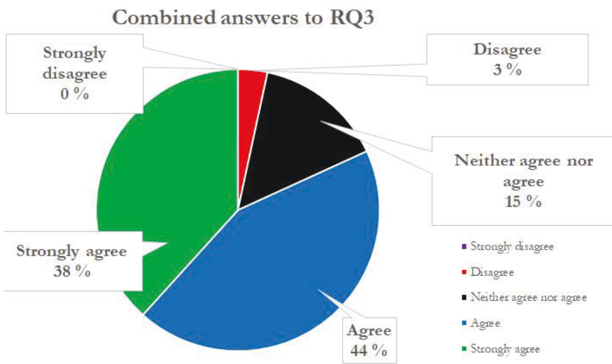

Fig. 7. Combined answers to the third research question (RQ3)

4 Discussions of results

Results of Figure 4 demonstrates that most participants answered in agreement to the six questions asked. This indicates a general positive outcome to the experiment. Besides, Figure 5 shows 53% in *agreement* and 34% *strongly in agreement* to the proximity of the plant simulation to reality, which answers RQ1 and consistent with literature on the subject [9&11]. Only 5% *disagreed* and 7% *neither agreeing nor disagreeing* to the closeness of the simulation to a real plant. Figure 6 has 43% *strongly in agreement* and 47% *agreeing* to the effectiveness of learning through the SGs-IVE technology. Only 1% *disagreed* and none *strongly disagreed*. This indicates that learning through SGs-IVE in the 3-D GPP is truly effective. Regarding the suitability of the technology in terms of user-friendliness and preference for this training, results in Figure 7 shows that 38% of participants *strongly agreed* and 44% *agreed* to this question. Only 15% *sat on the fence* and 1% disagreed.

5 Conclusion

This paper pragmatically utilizes serious games in an immersive 3-D gas-powered plant engine simulation. The purpose was to analyze the prospects of the technology for improving learning during safety training. Participant's combined results demonstrates that indeed the application of 3-D simulation-based technology has enormous potential in optimizing safety training. Besides the technology being suitable for training in a gas-powered plant model, results also indicated preference for simulation-

based safety training to conventional methods. Likewise, it was realized that learning during the training was authentic and interesting. This is consistent to results of the successes of SGs-IVE employed in some high-risk industries such as mining, construction and aviation [6&11]. That the entire exercise was worth the time spent for the training.
Despite these promising results, the research is however limited to filter replacements on GPP engines and cannot be generalized to other maintenance tasks on GPPs engines or to filter replacement on other heavy-duty engines.
Future research targets expanding the study to cover more safety countermeasures in other 3-D plants and factory simulations.

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Simulation-based assessments of fire emergency preparedness and response in virtual reality

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The current study aimed at evaluating the prospects of a three-dimensional gas power plant (GPP) simulation in an immersive virtual reality (IVR) environment for fire emergency preparedness and response (EPR). To achieve this aim, the study assessed the possibility of safety situational awareness, evacuation drills and hazard mitigation exercises during a fire emergency simulation scenario. The study likewise evaluated the safety and ergonomics of the environment while addressing this aim. We employed the virtual reality accident causation model (VR-ACM) for the assessment with 54 participants individually in IVR. Participants were grouped into two according to whether they had work experience in engineering or not. The obtained results suggested that IVR can be realistic and safe, with the potential for presenting hazardous scenarios necessary for fire EPR. Furthermore, the results indicated that there were no statistically significant differences in the perceptions of both groups regarding the prospects of IVR towards EPR.

Keywords: three-dimensional simulation; fire evacuation drills; ergonomics; simulation-based; immersive virtual reality; emergency preparedness and response

1. Introduction

Several compelling findings suggest that there has been a significant reduction in accident rates and an increase in safety awareness and litigation avoidance due to active and robust occupational safety practices [1–3]. Such emergency practices play important roles by ensuring that workers and employers are well equipped and prepared during hazards [2]. For this reason, industries and safety standards regard emergency preparedness and response (EPR) key to safety countermeasures [4,5]. Evidence also implies that the absence of safety training (ST), inadequate ST or a lack of relevant EPR contributes to increasing industrial injuries and fatalities during emergencies [2,4]. This notwithstanding, exposing workers to hazardous situations in live sections can be dangerous and too costly [6]. Consequently, the status quo of EPR logically, but rarely, involves practice by doing. However, an immersive virtual reality (IVR) technology can present three-dimensional (3D) computer simulations of objects, processes and events realistically for experiential and engaging encounter. IVR thus serves as a suitable option in situations that are either too expensive or impractical for direct hazard assessments necessary for EPR [5,7,8].

Grounded in methodologies, IVR thrives on the interest, realism and enthusiasm that subjects experience during an immersive encounter [9,10]. Furthermore, IVR provides real-time experience of computer-generated environments needed in simulation-based (SB) assessments [11–13]. Coupled to this, the technology presents information retention capabilities and benefits of experiential learning that exceed traditional methods [14–16]. Besides, evidence suggests that IVR is the best currently known method for assessments regarding hazard identifications and accident reconstructions [9]. Accordingly, Dale’s theory of the learning pyramid specifies between 75 and 90% absorption and retention as subjects ‘practice by doing’ [17,18]. For this reason, research related to employee development places IVR assessments in the category of practice by doing [19]. Thus, IVR serves as a useful alternative with captivating tasks towards enhancing EPR [20,21]. For this reason, IVR is currently gaining popularity in education and industry for risk assessments, design reviews and training [12,18,22]. Despite these growing potentials, applications of EPR are confined mainly to specific high-risk industries such as construction, mining, aviation and healthcare [16,23,24].

Traditional EPR methods are limited to classroom learning, and this has disadvantages in realism and without response to interactions [16]. Such traditional methods are rather common for risk assessments in gas power plants (GPPs), where the gas system has been noted as a high fire risk [16,21]. Therefore, activities of EPR in conditions with no accidental exposure renders the practice minimally effective [2]. This study therefore targeted investigating the

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prospects of EPR in a 3D simulation of a GPP in IVR. To achieve this aim, we employed the virtual reality (VR) accident causation model (ACM), which incorporates a series of events for triggering fire outbreaks. This model was employed for designing and implementing fire EPR that constitutes situational awareness (SA), fire evacuation drills (FED) and fire hazard mitigations. We further formulated four research questions (RQs) for testing the prospects of the exercise:

- RQ1: What levels of safety SA necessary for fire hazard detection can be attained in an IVR GPP simulation?
- RQ2: How effective will an IVR simulation environment of a GPP be for EPR?
- RQ3: How safe and ergonomically viable is the IVR environment for fire EPR?
- RQ4: Are there significant differences in the results of RQ1, RQ2 and RQ3 between participants with engineering work experience and participants without any engineering work experience?

We structured the rest of the article as follows to address these questions. In the next section, the background provides an overview of the pertinent literature on IVR, FED and hazard mitigations followed by the methodology and theoretical framework related to EPR. Next, we present the conceptual model of the study that describes the structure and empirical framework of the research. Subsequently, explanations of the experiment procedure and data gathering methods are presented. Thereafter, results are presented that elaborate and discuss the research findings regarding the four hypotheses. Finally, the study concludes in retrospect with theoretical as well as practical contributions and implications while examining the study limitations and suggestions for further research.

2. Background research

Fire EPR constitutes fire hazard identification and risk assessments, and relies on the requirements of Occupational Health and Safety Management Systems (OHSMS) enshrined in Standard No. ISO 45001:2018 [25] for the prevention of accidents and safety practices [26]. For this reason, it is mandatory for an International Organization for Standardization (ISO)-certified facility to ensure that all emergency preparedness plans, training and provisions are developed and assessed continuously for the health and safety of workers, employers and visitors [26].

Factory EPR includes adequate emergency exits, as well as accessibility to the exits, stairs and walkways in preparation for exiting the facility during emergencies [27]. Coupled to these, the requisite knowledge, skill and experience for exiting a facility are vital for accident prevention and survival during emergency evacuations [22]. These are outlined as follows:

- familiarity with the environment, emergency safety procedures and exits;
- realization of situations that necessitate evacuation;
- understanding of the basic guidance during and after emergencies;
- emergency hazard mitigation procedures [7,11,26].

2.1. *Safety evacuation assessment*

Several issues require consideration when designing facilities regarding safety evacuations in EPR. Some of these are as follows:

- evacuation drills do not have to be a boring repetition of annual lectures [6,27];
- transfer of tacit safety knowledge can be a major challenge [6];
- although VR provides state-of-the-art methods for EPR, it should never completely replace traditional classroom training [16];
- despite the interesting and authentic learning outcomes that VR provides, applications for EPR in immersive environments require basic gaming skills which can be challenging to some participants [27].

2.2. *Immersive VR environments*

Complete immersion in a 3D simulation environment is possible through a stereoscopic head-mounted display (HMD) headset built with gesture and weight sensors to attain true interactivity for both virtual and constructive (VC)-type simulations [10]. Embedded in the HMD are several sensors for detecting and tracking users' orientation to enhance the immersive experience [7]. This implies that users of the VR technology can navigate from one place to another as well as manipulate objects and receive sensory (visual and auditory) feedback [19,28]. As a result, simulated 3D images, scenarios and sounds in IVR create a feeling of presence for real-time response [29]. Presence in a simulation context refers to the experience that one immersed in the virtual environment receives while physically present in another [9,29]. IVR succeeds in this manner by interacting with simulations of real-world scenarios while providing real-time learning responses [30,31]. Consequently, major industries in automobile, construction and aviation employ immersive technologies for training and risk assessment with success [10,24]. IVR and computer simulations are also useful in determining accessibility of facilities during emergencies [19], as well as for improving user ergonomics [8]. For this reason, the technology enables participants to identify hazardous situations while implementing appropriate safety countermeasures during chaotic real-life situations [6,31], thereby making it suitable for providing experiential encounter for skill enhancement [3,12]. Evidence also suggests that IVR simulations are engaging and interesting; as a result, applications provide participatory, pedagogical and behavioural learning outcomes that promote cognitive learning [10,22,23].

2.3. Simulation-based fire evacuation exercise

According to Kinateder et al. [32], three vital issues require consideration when setting up IVR exercises:

- the possibility of simulation-induced sickness (SS);
- ergonomics of the environments and gadgets;
- validation of the effectiveness of the exercises for real-life emergencies [32].

These provide a useful basis for designing and implementing IVR environments successfully for fire safety evacuation exercises [27]. Scholars have long administered the simulator sickness questionnaire (SSQ) to participants after SB experiments to determine SS [20,33,34]. Bhide [27] developed a framework for fire evacuation training using a desktop computer with the mouse and keyboard as controllers. The work employed the SSQ for evaluating the safety of the simulation environment. Obtained results indicated that participants exhibited better sustained attention and interest in the virtual realm than in the conventional classroom environment. In the same way, Rzeźniczek et al. [34] employed the SSQ for determining the levels of SS before and after a motion car simulator experiment. Likewise, Cha et al. [20] developed a VR fire simulator that displays fire dynamics based on data conversion techniques for training in fire response and rescue activities.

2.4. Presence in fire evacuation simulations

Timely evacuation procedures are important during emergencies in GPPs. This is heightened by how quickly and effectively a hazardous situation can be brought to the awareness of occupants of the plant [2]. For this reason, it is prudent to access levels of SA in immersive applications where emergency actions are required, such as in fire EPR [9]. A method widely utilized for assessing the level of presence is the Slater–Usoh–Steed questionnaire (SUSQ). The SUSQ is also frequently employed for evaluating awareness during training and risk assessments in simulation environments [7,23,35]. Interestingly, SB EPR in combating fire indicates that participants exhibit similar levels of learning in simulations to those in actual scenarios [7,36].

3. Methods

3.1. Research framework, hypotheses and assessment model

This section explains our EPR assessment model, hypotheses and research methodology, as shown in Figure 1. The model is built on a modified version of Bhide's [27] virtual 3D emergency fire evacuation training design, and also based on Dhalmahapatra et al.'s [12] VR-ACM comprising SB modelling, recognition of impending hazards and, finally, assessments. Although the ACM was originally designed for accident investigations, the VR-ACM is as suitable for assessing awareness and preparedness for fire emergencies [12,37]. Figure 1 consists of the following three parts and elaborates our study methodology:

- identification (i.e., recognition of the problem, RQs and hypotheses formulation);
- virtual environment, explaining the experiment procedure characterized by a maintenance task in IVR, accident causation, awareness of the situation, evacuation and hazard mitigation in the GPP simulation;
- evaluation of the experience, where participants answer the 15-item questionnaire regarding the exercise.

The evaluation, firstly, assesses participants' levels of SA that answer RQ1 as stated in H_1 (see Section 3.5 for details of H_1–H_4). We adapted related questions from the SUSQ that are extensively utilized in analysing SA. Next was the evaluation of H_2 in answer to RQ2, which assesses the effectiveness of FED and the hazard mitigation exercises in IVR. In this way, H_2 also evaluates the success or otherwise of the immersive exposure. The questionnaire for assessing H_2 was derived from Kirkpatrick's three-stage model for evaluations. Thirdly, RQ3 seeks to discover the safety and ergonomics (SE) of the simulation environment as stated in H_3 and relies on the SSQ for measuring VR-induced symptoms and effects (VRISE). VRISE occur if one exposed to a virtual simulation generates symptoms like motion sickness. The SSQ was designed by Kennedy et al. [38] and measures three distinct factors: nausea, oculomotor disturbance and disorientation. Notably, whereas the main hypotheses of this study (i.e., H_1, H_2 and H_3) focus essentially on SA, FED with mitigation and ergonomics, and are related to the ACM in the immersive environment, the moderator hypothesis (H_4) relies on the independent variable work experience in engineering. Therefore, H_4 evaluates the differences in answers to RQ1, RQ2 and RQ3 between participants with engineering work experience and participants without any engineering work experience.

Although literature served as the main source of information for this model, we were privileged to interview two experts in EPR about GPPs, on preparedness for emergencies and FED. Key issues obtained in the interviews highlighted gas leakage and the location of the main gas valve outside the plant. Other points gathered were the importance of early recognition of fire hazards in the assessment for possible mitigation. On the other hand, information gathered about the evacuation drills during

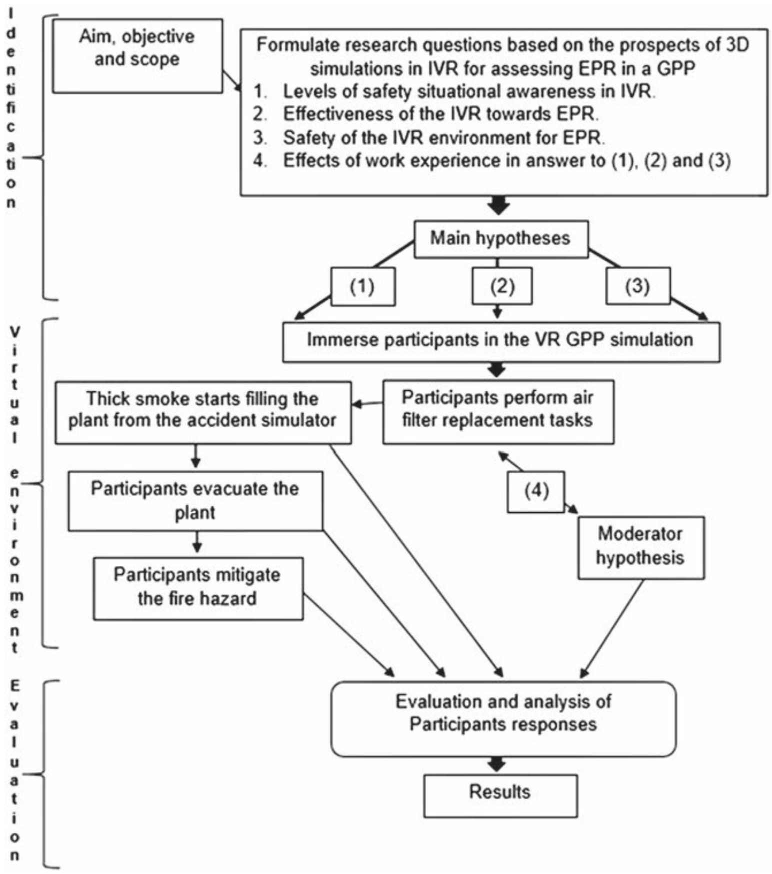

Figure 1. Conceptual model of the study.
Note: 3D = three-dimensional; EPR = emergency preparedness and response; GPP = gas power plant; IVR = immersive virtual reality; VR = virtual reality.

the interviews dealt with communicating evacuation routes precisely before the drills and keeping the emergency plan up to date as well as providing adequate evacuation routes in the plant. These interviews enabled a more practical and realistic perspective to our virtual assessment model.

3.2. *The 3D immersive environment*

We developed our model for the plant with the aid of Fusion 360 version 2.0.9305 3D designing software and Unreal real-time game engine version 4.2 (UE4) that enabled creating simulations for the assessment. A Windows 10 Enterprise, 64-bit computer (ASUS, Taiwan) with an Intel Core i7-7700 Quad-Core processor at 3.6 GHz processing speed, having a GTX 1070 graphics card, powered the simulation. Two base stations (HTC Vive, China) relayed the plant simulation for participants to experience full immersion through an HMD and hand-held controllers (HTC Vive, China) with gesture sensors. The 3D simulation environment constituted a conceptual power plant, powered by three gas-fired engines.

3.3. *Assessment procedure*

The exercise began by first explaining the IVR environment, the tasks for the assessment and the personal emergency evacuation plan (PEEP) individually to all participants and allowed questions. The explanation also covered the IVR techniques regarding the HMD, controllers and drills as well as the questionnaire based on the EPR. Participation was voluntary, and confidentiality of the participants' identity was guaranteed. Upon agreement, both researchers and participants signed the informed consent form. Consequently, we collected participants' demographic information (Table 1) based on the anonymity and non-traceability criteria. Participants then wore the HMD head set, which allows 3D views of the simulated plant depending on the angle of sight. One of the participants had to discontinue the exercise after commencement since she could not see clearly through the HMD headset without her eyeglasses. The participants were then divided into the two groups according to their work experience in the field of engineering. This was because those who work in the engineering field are usually perceived to have some

Table 1. Demographic characteristics of study participants.

Demographic factor	Value
Age	18–28 years = 37 (68.52%), 29–39 years = 13 (24.07%), 39 years and older = 4 (7.41%)
Gender	Females = 13 (24.07%), males = 41 (75.93%)
Study level	First degree = 22, master's degree = 24, PhD = 8
Work experience	Participants without engineering work experience = 21 (38.89%), participants with engineering work experience = 33 (61.11%)

occupational safety knowledge or skills that are relevant to the current exercise.

3.4. *Fire evacuation and mitigation assessments*

The exercise in VR proceeded as follows:

- Both groups of participants were initially tasked with replacing the air filter of the third engine in the plant.
- During the filter replacement, the accident simulator triggered dense smoke because of fire eruption, which quickly populated the plant. This smoke was caused by gas leakage from the second engine in the plant.
- Upon sensing the emergency, participants were to evacuate the plant through the nearest door exit.
- After safely exiting the plant, participants were then tasked to isolate the power source by shutting the emergency valve.

These procedures were to be implemented through the premeditated PEEP, which incorporated identification of key escape routes with specific evacuation procedures and, finally, mitigation of the impending hazard. Detection of fire was purely by the awareness of participants and the model purposefully omitted gas detectors, alarms and sirens. The reason for this was to test levels of SA at the onset of the fire hazard. The simulated smoke hazard was relevant to the awareness and preparedness for fire emergencies since smoke inhalation is attributed as the leading cause of death during fire outbreaks [11]. Secondly, early detection of gas leakage with subsequent mitigation is necessary in GPP EPR to avert the possibility of explosion. Evacuation from the plant (Figure 2) was possible with the aid of handheld controllers that enabled participants in the operating equipment to manoeuvre, walk and open doors in the plant. The second part of the assessment involved mitigation of the fire outbreak. The mitigation process involved moving outside the plant and closing the gas valve as seen in Figure 3 to stop fuelling the ignited fire.

3.5. *Data collection and analysis*

The 54 students who took part in the assessment were from four universities in Vaasa, Finland (Table 1). We targeted four universities to obtain a wide diversity of participants. Table 1 also presents the demographics of the participants who comprise the two groups: students without any engineering work experience; and students with some engineering work experience. The exercise took place between November 2018 and February 2020 at the Technobothnia Virtual Reality Research and Development Laboratory, which is equipped with state-of-the-art equipment needed for the exercise. After performing the task outlined in Section 3.4, participants finally evaluated the prospects of the exercise as well as the SE of the IVR environment. Assessment was obtained on a 5-point Likert scale ranging from 1 = *strongly disagree* to 5 = *strongly agree*.

3.5.1. *Analysis of safety SA*

SA in the context of occupational safety refers to the awareness of individuals to the surrounding conditions due to their ability in identifying potential risks and hazardous situations ahead of possible dangers [9]. Notably, SA is relevant in situations where quick information processing is vital with serious consequences for inaction or poor decisions [15]. The three levels of SA considered for this assessment, according to the SUSQ guidelines [24], constitute: level 1, perception potentials of hazardous conditions in the environment; level 2, comprehension of the condition; level 3, links to future projections in the event of the perceived condition occurring. We posit the following in answer to the levels of SA that are attainable in the plant simulation as stated in RQ1:

- H_1: substantial levels of SA necessary for fire hazard recognition are attainable in an IVR GPP simulation environment.
- Measures: we measured participants' level of SA (Q1–Q5) by portions of the SUSQ that, as aforementioned, measures and ascertains the depth of presence and exposure in virtual environments [24]. Table 3 presents the data obtained for the SA. We obtained Cronbach's $\alpha = 0.725$.

3.5.2. *Assessment of the evacuation exercises*

The evacuation exercise consisted of three parts; recognition, response and evacuation [7]. Participants rated their experience by their ability to evacuate from the plant from the time the fire broke out, by their ability to sense the danger and find the nearest exit for evacuation within the maximum evacuation time limit of 2.5 min as stipulated in the fire safety guides for factories and warehouses [39]. Closing the main gas valve (Figure 4) that pumps natural gas to the engine successfully halts the fire hazard and concludes the assessment. In answer to RQ2 linked to the

Figure 2. A participant evacuating the power plant at the onset of fire.

Figure 3. A participant closing the main gas valve to arrest the fire hazard.

Figure 4. Completion of the EPR assessment.
Note: EPR = emergency preparedness and response.

effectiveness of the evacuation and mitigation exercises, we hypothesize the following.

- H_2: compelling fire evacuation and mitigation exercises are feasible in IVR GPP simulations.
- Measures: to measure the effectiveness of the evacuation and mitigation drills in our questionnaire, we derived Q6–Q10 (Table 4) pursuant to Kirkpatrick's three steps for evaluating successes or otherwise of exercises. The steps are reaction (level 1), learning (level 2) and behaviour and results (level 3) [40,41]. These steps have been employed for measuring experiential learning effectively in virtual emergency evacuation exercises. We obtained Cronbach's $\alpha = 0.705$.

3.5.3. SE of the assessment environment

We combined questions of possible SS and user friendliness according to the SSQ to answer Q11–Q15. These questions, as explained earlier, consider disorientation and the oculomotor impact of VRISE as well as the ergonomics of the set-up. Oculomotor impact refers to fatigue, headache, concentration and the difficulty one encounters in focusing [23]. Besides, our simulation experiment was set up according to the health and safety instructions of the HMD safety regulatory guide in compliance with protecting the safety and well-being of participants during immersive exercises. Adhering to these regulations is essential, considering that a technology employed for assessing and promoting safety needs to ensure substantial safety levels during the assessments. For example, improper adjustment of the VR headset to a 'bad fit' on participants can lead to blurred images and poor optical presentation, which increases VRISE [15]. Secondly, it was necessary to provide supervision and adequate guidance to participants during the exercise to prevent the immediate danger posed to participants. The immersed participants are blinded to the natural environments during

Table 2. Descriptive statistics of measured variables.

Variable	Sample statistics N	M	SD	Minimum	Maximum
Engineering work experience	54	0.611	0.492	0	1.000
Situational awareness	54	4.226	0.485	2.200	5.000
FED/hazard mitigation	54	4.293	0.449	3.200	5.000
Safety and ergonomics	54	4.226	0.396	3.000	5.000
Overall perception	54	4.248	0.354	3.200	4.867

Note: FED = fire evacuation drills.

fully immersive exercises and this can lead to crashes or falls [42]. Thirdly, the total assessment tasks were scheduled to last less than 25 min per participant. This initiative was a measure we instituted in view of the positive correlation that exists between exposure time and VRISE [41]. The evaluation of SSQ and the ergonomics of the experiment answer RQ3, and we therefore posit:

- H_3: an IVR environment can be safe and ergonomically viable for assessing fire EPR.
- Measures: we measured any possibility of VRISE and the simulation environment ergonomics with portions of the SSQ [38]. Table 2 presents the descriptive statistics of measurements while Table 5 presents the results in answer to RQ3, which satisfies H3. We obtained Cronbach's $\alpha = 0.713$.

3.5.4. *The moderating factor 'engineering work experience'*

Whether a participant had some engineering work experience or not was the key factor employed in moderating H_1, H_2 and H_3, which correspond, respectively, to SA, FED and mitigation, and SE of the simulation environment. The difference in the responses between the two groups answers H_4. It was necessary to analyse H_4 given the general notion that work experience influences the safety response [43].

3.5.5. *Effects of engineering work experience on prospects of SB fire EPR*

It is commonly believed that engineering work experience correlates positively to safety culture and safety behaviour [4]. However, as previously noted, studies into the relationship between engineering experience and perception and the prospects of IVR towards EPR are silent. In unravelling this perception, we thus posit:

- H_4: participants with engineering work experience perceive IVR to be more beneficial for EPR than those without any engineering work experience.
- Measures: we measured the differences between the two groups by testing the independent-sample t test between the M of both groups for the three factors under consideration. This involves comparing the M results of H_1, H_2 and H_3, which represent SA, FED and mitigations, and SE, respectively, for both sample groups. The obtained results answers H_4. Table 6 presents the outcome.

3.6. ***Assessment evaluation***

We evaluated our model by analysing the responses to the 15 items presented in Tables 3–6. These tables answer H_1–H_4 according to RQ1–RQ4, respectively. Furthermore, we computed interaction effects of the independent variable 'engineering work experience' to test the simultaneous

Table 3. Results of SA for both participating groups.

Safety situational awareness		Response to H_1: situational awareness necessary for fire hazard recognition			
		Without WEE ($n = 21$)		With WEE ($n = 33$)	
		M	SD	M	SD
Q1	Presence levels in the simulation	4.095	0.625	4.061	0.747
Q2	Awareness levels while working	4.286	0.644	4.364	0.859
Q3	Awareness of the plant situation	4.524	0.602	4.333	0.854
Q4	Recognition of the fire hazard	4.238	0.539	4.061	0.789
Q5	Action upon recognition of hazard	4.191	0.602	4.182	0.528
Total		4.267	0.390	4.200	0.538

Note: SA = situational awareness; WEE = work experience in engineering.

Table 4. FED and mitigation results for both groups of participants.

Evacuation drills and mitigations		Response to H_2: feasible fire evacuation and mitigation drills in IVR			
		Without WEE (n = 21)		With WEE (n = 33)	
		M	*SD*	*M*	*SD*
Q6	Personal emergency evacuation plan	4.286	0.717	4.212	0.740
Q7	Evacuation routes and signs during fire	4.333	0.483	4.182	0.846
Q8	Mitigation action to arrest the hazard	4.429	0.508	4.182	0.635
Q9	Applicability of skills to life situations	4.286	0.717	4.515	0.566
Q10	Interesting and engaging experience	4.286	0.644	4.273	0.626
Total		4.324	0.440	4.273	0.460

Note: FED = fire evacuation drills; IVR = immersive virtual reality; WEE = work experience in engineering.

Table 5. Results of SE for the two groups.

Safety and ergonomics		Response to H_3: safety/ergonomics of the immersive exercises and environment			
		Without WEE (n = 21)		With WEE (n = 33)	
		M	*SD*	*M*	*SD*
Q11	Safety of VR technology/environment	4.143	0.478	4.152	0.619
Q12	Ease of the controls/navigation in the VR	4.476	0.680	4.364	0.549
Q13	Favourable learning conditions in the VR	3.952	0.669	4.152	0.566
Q14	Feeling uncomfortable during exposure	4.238	0.539	4.303	0.637
Q15	Feeling uncomfortable after exposure	4.143	0.655	4.273	0.452
Total		4.190	0.435	4.248	0.374

Note: SE = safety and ergonomics; VR = virtual reality; WEE = work experience in engineering.

effects on the dependent variables SA, FED and mitigations, and SE. This was for the purpose of evaluating the impact of the dependent variables on the independent variables [44]. We further computed the independent variables in two successive steps to control possible confusing effects. During evaluation, answers to Q14 and Q15 in Table 5 were reverse coded due to the negative connotation present in the question format. SAS EG version 7.1 was utilized in performing the analysis for both population groups. To ascertain the significance of *M* values in Table 6, we employed a 95% confidence interval according to Cox and Lewis [45] throughout our analysis.

4. Results

This section presents the results of the three assessments as provided by the participants, which answer RQ1–RQ3 as hypothesized by H_1–H_3, respectively, and are moderated by RQ4 for H_4. These results are presented in Tables 2–5, which present the measured average values of responses for identifying the central position within each group of answers. Next, four independent-sample t tests were conducted to determine the similarities between the results of participants with some work experience and participants without any work experience, which answers RQ4, as presented in Table 6.

Table 6. Results of independent-sample t tests between variables.

Variable	*M* of WEE	*M* of no WEE	Mdn	95% confidence interval	*t*	*df*	*p*
SA	4.200	4.267	0.067	[−0.207, 0.340]	0.489	52	0.627
FED	4.273	4.324	0.051	[−0.203, 0.308]	0.404	52	0.688
SE	4.248	4.190	0.058	[−0.281, 0.166]	−0.521	52	0.605
MOP	4.240	4.26	0.02	[−0.180, 0.220]	0.199	52	0.843

Note: FED = fire evacuation drills; Mdn = median; MOP = mean overall perception; SA = situational awareness; SE = safety and ergonomics; WEE = work experience in engineering.

4.1. Descriptive statistics

Table 2 presents the combined results for both groups regarding the *M* and *SD* of the empirical ranges for the key study variables of all 54 participants. The table also presents the results of the general impression of all respondents to the entire assessment at the overall *M* perception row. We achieved a measure of reliability in internal consistency of 0.706.

4.2. Responses to the levels of SA

Table 3 presents the levels of SA in the immersive environment according to the SUSQ, which also elaborates the individual questions for SA and answers H_1. We also computed participants' preferences according to the Likert-scale items in percentages due to the low number of participants. Overall, 90.74% of responses from both groups combined scored 'strongly agree' or 'agree' to the questions according to Table 3. Only 1.85% of the responses registered 'strongly disagree' or 'disagree', and 7.41% were undecided regarding the question which answers H_1.

4.3. Results of FED and mitigations

The results of the questions pursuant to the effectiveness of FED and mitigation drills for both groups of participants are presented in Table 4. These questions concerned participants' interest, skill and knowledge acquired, which synchronizes to Kirkpatrick's three steps for evaluations and answers RQ2. The total responses of both groups to the questions presented in Table 3 and Table 4 represent the overall success or otherwise of the assessment regarding the effectiveness of IVR for EPR. The analysis of the results from Table 4 according to the independent-sample *t* test produced results of 0.404 with $p = 0.688$ (Table 6) for answering RQ4.

4.4. Results of SE in IVR

The results obtained from the questions related to SE according to H_3 answers RQ3, and Table 5 elaborates the SE of the entire IVR exercise. In this case, the results present findings on whether the simulation environment was safe for EPR. Specifically, Table 5 presents participants' perception of SS because of VRISE. This perception, as explained earlier in Section 3, assessed the three general categories of VRISE from the SSQ with the ergonomics of IVR.

4.5. Work experience in engineering on prospects of SB fire ST

Regarding H_4, which purports that participants' work experience in engineering affects their perception of the prospects of IVR for EPR, we conducted an independent-sample *t* test on all three dependent variables – i.e., SA, FED and mitigation, and SE – based on the independent variable 'work experience in engineering'. This analysis measures *M* of both groups for the three dependent variables to determine whether evidence exists to suggest any significant differences between the perceptions of participating groups. We obtained the individual values of the three factors as presented in Table 6, with an overall $p = 0.843$ at a significant α level of 0.05.

5. Discussion

5.1. Examination of the obtained results

This section explains the results presented in Section 4 regarding the effectiveness of the IVR simulation environment for SA, preparedness and response for fire emergencies, and the possible effect of engineering work experience on the examined factors. These were investigated as SA, FED and mitigation, and SE during the assessment. The obtained results individually indicated that the main ingredients of a fire EPR plan – safety awareness, safety knowledge and safety mitigation skills – can be mimicked in a real-time IVR simulation environment for improving plant safety.

5.1.1. SA analysis in IVR

Referring to the results presented in Table 3 that answer RQ1 about feasible levels of SA necessary for fire detection, the overall *M* of 4.267 (from 1 = *poor* to 5 = *excellent*) implies that a high level of SA was experienced during the immersive encounter by both participating groups. These values do not also vary greatly from *M* according to the obtained total *SD* of 0.390 and 0.538, respectively, for both groups. This implies an appreciable level of agreement amongst participants, and also reflects significant comprehension between time and space for participants during the immersive experience, which affirms H_1, in answer to RQ1, that substantial levels of SA necessary for fire detection can be attained through a 3D simulation of a GPP in an IVR environment. SA was assessed based on the underlining factors of perception, comprehension and projection. These three factors are the main ingredient that the SUSQ assesses. The results also suggest that the plant simulation set-up provides an enabling environment for assessing risks and for recognizing hazards in the intended plant design. Besides, these results conform to previous findings in the field by, e.g., Slater et al. [33], who employed the SUSQ to analyse the relationship that exists between physiological responses and breaks in the presence of 20 participants and found a significant difference between the experimental phase and the actual training. Similarly, Giglioli et al. [23] compared the sense of presence and performance with the SUSQ for subjects in an ecological task, while Lee Chang et al. [9] likewise analysed the impact of simulation against lectures for training by employing the presence tool. This suggests that IVR is feasible for SA and therefore applicable for EPR in a plant simulation. Such assessments are critical for ensuring safety in high-risk fire-prone facilities. The exercise has also enabled participants to understand the importance of emergency preparedness, for maintaining high safety awareness of one's working environment. Implications are that IVR can present 3D simulations realistically for experiencing hazardous situations necessary for EPR. Such situations make it possible to act accordingly and receive real-time response for learning, which hitherto was not possible with traditional classroom methods for comprehending SA during risk assessments.

5.1.2. Analysis of FED and the mitigation exercises

The results for H_2 with respect to RQ2 concerning the effectiveness of FED and the mitigation drills also indicate a positive trend. Primarily, the combined high M of 4.293 realized in Table 2 for both groups as well as the total M values of 4.324 and 4.273 presented in Table 4, according to the Likert scale from 1 to 5 based on Kirkpatrick's evaluation model, significantly indicate a positive trend. This suggests that the immersive environment can be effective for FED and mitigation, which thus confidently accepts and affirms H_2. The results also revealed that participants received full experience of close to real scenarios in a safe and controlled environment without any distractions while immersed. Besides, the exercise has demonstrated that simulating a real plant fire hazard with immediate feedback for realizing the consequences of following or not following safety procedures provides the platform necessary for experiential learning. This implies that specific hazardous scenarios can be simulated for more critical IVR safety assessments before definitive construction of the intended facility. Moreover, the combined responses register that the immersive experience offers participants the privilege to prove their knowledge at the onset of a fire emergency and receive instant feedback. Furthermore, the immersive encounter has exposed participants to the need of preparedness for decisive actions during a fire emergency. These results are also consistent with research that employs IVR towards FED and mitigation, e.g., Smith and Ericson [36], Tian et al. [40], Torda [35], Patel and Dennick [46] and Lee Chang et al. [9].

5.1.3. SE assessment of the IVR environment

This section explains the results obtained while assessing the SE of the IVR environment for EPR. Regarding the possibilities of VRISE, which answers RQ3, the M values of 4.190 and 4.248 obtained for both participating groups according to the SSQ results presented in Table 5 suggest appreciable levels of safety and ergonomic viability experienced by participants during the immersive exercise. These values were likewise obtained with the 5-point Likert scale as was employed in assessing responses to RQ1 and RQ2. The values advocate participants' perception, which affirms H_3 that the immersive environment provided safe conditions with negligible effects of SS, usually present in VRISE, and therefore is suitable for fire EPR. It is also necessary to explain that the high values obtained from participants presented in Table 5, regarding the safety of the VR environment, were partly due to the safety measures employed in the experiment.

The following explains the measures in accordance with the safety and regulatory guidance (HTC Vive, China) for the HMD headset [47]. Firstly, we adhered to the minimum age of 18 years during our inclusion criteria, purposefully to prevented possibilities of seizures, which according to the manual are a factor common in children [47]. Secondly, a virtual translucent wall in the immersion served as a guide to participants despite the physical guidance researchers provided for each participant throughout the exercise. This inherent feature in the HMD set-up is a safety guide for informing users of the safe area, in the actual world, to prevent the possibility of falling or crashing into an object. Thirdly, we ensured that the HMD was secured comfortably on each participant before running the simulation. This was to prevent poor optical presentation and blurred images since both factors increase SS. Similarly, we prevented hearing discomfort or loss by keeping the volume of the earpiece moderate, considering that listening to loud sounds for a long time can damage the ear. We also limited the total exposure time to 25 min according to the HTC factory-recommended exposure time of less than 30 min per immersion with a 10-min break if needed [47]. Additionally, we ensured that the headset was cleaned by sanitizing after every immersion, considering that the HMD is usually worn tightly on the user's scalp. Adhering to these safety measures contributed to increasing the safety and eliminating the health and risks potentials of the IVR environment. It was interesting to note that, apart from one participant who had to pull out of the assessment due to an eyeglasses issue, the remaining 54 participants completed the assessment successfully. This, coupled with their tabulated responses, indicates that there were no substantive symptoms such as fatigue, nausea, drowsiness, increased salivation, visual abnormalities like eye strain and double vision or any symptoms similar to motion sickness.

5.1.4. Effects of engineering work experience

This section explains the results obtained for RQ4, which sought to compare the results between the two participating groups. To achieve this, we compared the M of SA, FED and mitigation, and SE representing H_1, H_2 and H_3, respectively, for both groups to determine any significant differences between their perceptions. For the SA, since $p = 0.6272$ (Table 6) is greater than $\alpha = 0.05$, we can conclude that no differences exist between the perceptions of both groups regarding SA. Secondly, the results obtained for FED and mitigation provided $p = 0.688$, which is equally greater than $\alpha = 0.05$. This contrast also signifies no compelling differences between the two groups regarding answers to RQ2. Considering the results of SE, which answer RQ3, the obtained $p = 0.605$ in Table 6 is also greater than the significance $\alpha = 0.05$. This also indicates that no statistical differences exist between the perception of both groups to the levels of SE. Likewise, the overall M perception of the combined responses of all three RQs, which answers RQ4, according to H_4, shows $p = 0.843$ which is much greater than the significance $\alpha = 0.05$. We can therefore conclude that there are no significant differences in the perception between the two groups for all three factors under consideration. In this vein, H_4, which purports that work experience in engineering affects the perception of the prospects of IVR for EPR, lacks substance and we can therefore confidently reject that notion. However, these similarities signify that the application of 3D simulation in IVR for EPR is not only suitable for those who have prior safety engineering exposure, but is equally suitable for novices.

5.2. *Results validity*

We employed a purification process to check the construct validity of our results. Secondly, our data have undergone other purification processes comprising three stages:

- A check on the convergent validity; this was met since p values for all items presented in Table 6 were always high and significant. Besides, the standard errors of these items were relatively low.
- A check on discriminant validity based on the examined 95% confidence interval for each pair of constructs did not include 1.00 at any instant, as Anderson and Gerbing [48] explain.
- We verified the construct reliability, which was satisfactory as all constructs evaluated exhibited Cronbach's α greater than 0.70. Collectively, the combined results demonstrate that common method bias was unlikely to be a cause for concern in the current study.

Furthermore, the results for H_1, H_2 and H_3 are consistent with IVR simulation in related research works, e.g., Bilotta et al. [49] Bhide [27] and Nedel et al. [28], all of whom discovered that participants perceive SB fire evacuations in immersive environments positively. Likewise, Rzeźniczek et al. [34] and Borrego et al. [37] produced appreciable values when evaluating the effects of VRISE during assessments by administering the SSQ.

5.3. *Limitations of the study*

This study has some limitations worth noting. As a latitudinal study, the research did not test participants' retention of lessons over any period. Several studies, e.g., Berg and Vance [29], Bilotta et al. [49], Lee Chang et al. [9] and Cha et al. [20], however, have conducted such longitudinal studies and there is therefore ample literature to support the superiority of participants' retention in the IVR environment over conventional classroom methods. Another limitation was that the detection of the fire hazard in the form of gas leakage that caused smoke in the simulation was possible only by sight and not by smell, and therefore has the potential to limit SA in the IVR environment. Besides, the plant simulation eliminated some dynamic automated processes in an actual GPP that were not relevant to this assessment but could affect the overall plant EPR. Next, participants were able to move superficially in the plant simulation during evacuations by hurdling over objects and stairs as well as jumping from the first floor to the ground floor in seconds. This is a practice that is not feasible in reality. Despite these limitations, the study nonetheless offers valuable contributions for enhancing applications of IVR towards industrial fire EPR practices.

5.4. *Contributions and implications*

The study contributes practically and theoretically towards EPR in several ways:

- The study has demonstrated that participants in an IVR encounter of a 3D simulation environment can experience real-time emergency scenarios for safety preparedness and response at the factory conceptual stages. This is possible anywhere away from the location of the intended facility.
- By providing proactive emergency and realistic scenarios, with engaging and interesting fire encounter, the study adds to research findings regarding IVR environments for enabling adequate preparedness and planning, which helps promote factory safety measures.
- Specifically, the study demonstrates the importance of safety SA for survival during plant fire emergencies. This underpins the essence of awareness of immediate threats even when engaged in factory demanding tasks.
- To the evolving scientific literature concerning the utilization of IVR for fire emergency awareness and response, the study demonstrates that realistic situations and environments are possible, and can therefore influence safety designs at the factory conceptual stages.
- Likewise, the study contributes to the prospects of SB risk assessments as well as plant hazard identifications that are both key to EPR. According to Standard No. ISO 9001:2015 [50] and Standard No. ISO 45001:2018 [25], EPR ought to continuously improve for the purposes of promoting plant safety countermeasures [26]. We are therefore confident

that the findings presented in the experiment will spur detailed research in this direction.

Despite these potentials, and in view of the numerous limitations, however, the study does not propose that the application of IVR for fire EPR should be a complete alternative to the status quo of fire safety assessments. Rather, it should serve as a complement to traditional EPR assessments.

6. Conclusions

A VR-based fire emergency simulator has been developed and utilized in assessing the prospects of IVR for fire EPR. The model presents real-time 3D images, processes and interactivity necessary for experimentations during fire emergencies. The assessment constituted the following:

- safety SA, which studied the capacity of the immersive environment in presenting realistic hazards regarding the perception, comprehension and interpretation of a fire emergency;
- FED and mitigations, which assessed the viability of the immersive environment for EPR;
- SE of the IVR plant simulation environment.

The main purpose of the study was to examine the suitability of IVR for EPR. Two groups participated in the assessment: student participants with no engineering work experience; and student participants with some work experience in engineering. The reason for these groups was to analyse any differences in opinion for the three factors necessary for EPR. Results of the assessment revealed that, indeed, substantial levels of SA necessary for fire hazard identifications were feasible in IVR. This was because participants experienced appreciable levels of presence, interactivity and fire hazard mitigation during the assessment while immersed. Thus, our results conclude that the IVR technology is capable and suitable for revealing details of a plant design with the necessary dynamisms for fire EPR. Our experiment, notwithstanding, revealed no significant differences between perceptions of the two participating groups, which implies that the immersive technology is suitable for both groups equally for assessing EPR. The study also confirmed that a simulation environment can be safe and ergonomically suitable for fire emergency assessment provided the VR equipment, safety instructions, protocols and safety procedures are adhered to.

6.1. Suggestions for future research

In the future, we hope to extend a fully immersive VR-ACM for risk assessments and hazard mitigations in areas where the technology is lacking. We also hope to train two groups of participants in a prospective cohort study – one group in an actual factory and the other group in an immersive virtual environment of the same factory simulation – and verify the differences in safety culture immediately after training and over a period. The results will enable us to verify the applicability of the technology for more safety-related practices.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Effects of an engaging maintenance task on fire evacuation delays and presence in virtual reality

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ABSTRACT

The current study aims to investigate the capability of occupants of a powerhouse simulation to sense a fire and initiate evacuation while engaged with a task. For this reason, the study involved the maintenance task of replacing the air filter of a gas-powered engine through a series of instructions. The virtual reality-based accident causation model (VR-ACM) consisting of 3D modeling and simulation, accident causation, and safety training was adapted to address the study's aims. Two groups of participants were immersed in the virtual realm as occupants of the powerhouse to determine the pre-movement time and the evacuation duration under distinct scenarios. The first scenario constituted the experimental group ($n = 26$), who were assigned to replace the filters, while the second scenario (control $n = 26$) performed no task before the fire outbreak. An independent samples *t*-test revealed a significant difference in the pre-movement time of the groups, which suggested a decline in the perception of the experimental group due to the task. Further assessment revealed a consequential transfer of the delay at the pre-movement phase to the evacuation delay of the experimental group from the powerhouse. Secondly, the differences in *interactivity* implied that the experimental group exhibited a higher level of *involvement* and *distraction* in the *Presence* measurement than the control group. To this end, a virtual reality (VR) environment's performance and real-time functionality during a maintenance task simulation have been experimented with in an emergency fire evacuation scenario to ascertain safety concerns.

1. Introduction

Natural gas-fired powerplants are essential power solutions that contribute to a quarter of the world's electrical power supply [1]. However, the operation and maintenance of such powerhouses are inherently hazardous due to the possibility of leaking high-temperature gases or harmful gases that can cause a fire outbreak or asphyxiation, respectively [1,2]. Therefore, incorporating adequate safety measures and standards is critical in designing powerhouses to promote safety [3]. Despite such efforts, fires still occur. Accordingly, early recognition by occupants for evacuation is an essential component in *performance-based fire safety engineering designs* to protect people, property, and the environment from fire [4].

Moreover, incident assessments focusing on evacuations during fires suggest a correlation between delayed evacuation and fatality rates [5,6]. Furthermore, evidence from actual fire evacuations indicates that people are often engaged in non-evacuation tasks during fire emergencies. For example, some people gather personal belongings, talk with others, and seek information before initiating evacuation [7,8]. Other studies also affirm that the psychological reaction of evacuees before evacuation can affect the evacuation duration [8]. For these reasons, the importance of frequent evacuation drills and risk assessments in high-risk facilities has never been over-emphasized [1].

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Against this background, and since it is unethical and unjustifiable to directly subject humans to fire effluents for estimating the duration of compromised tenability, the status quo of traditional fire evacuation drills do not involve actual fire emergencies. This renders such safety evacuation sections monotonous, uninteresting, and minimally effective [2,9,10]. Secondly, it is not prudent to measure the evacuation tenability due to an occupational task during actual fires [5]. Thirdly, information gathered from firefighters does not consider functions that have no direct effect on the courses of the fires [6]. Therefore, the established methodology for evaluating the safe time on occupant pre-movement has not been validated experimentally [9,11]. However, the enthusiasm and realism virtual reality (VR) generates during immersion coupled to the possibility of exposing participants to a safe virtual fire encounter at diverse locations and at multiple times provide a suitable means for measuring the time at which compromised tenability may occur [2,12,13]. For this reason, there has been growing interest with evidential progress in applications of VR simulations for risk assessments and skill enhancement in fire evacuations, awareness, and preparedness for fire emergencies. For example, Markwart et al. (2019) [14], Cao et al. (2019) [15], and Zhou et al. (2020) [16] experimented with evacuees' behavior during way-finding in VR. Other VR-related studies involved crowd congestion amid fire evacuations by Wang et al. (2021) [17], route turning on evacuation performance, Zhang et al. (2021) [18], and Kwegyir-Afful et al.'s (2021) fire emergency preparedness, response, and mitigation [2]. Furthermore, measuring the level of *Presence* in a virtual realm for participant-related experiments is necessary to assess the simulation's logical (face) validity [19]. Accordingly, various studies, for example, Zou et al. (2017) [20] and Kritikos et al. (2020) [21], have established that engaging participants in emergency evacuations increase their perception of *Presence* in the virtual environment.

However, there has been no attempt to investigate the impact of an engaging occupational task before an emergency fire to assess the pre-movement time due to the task in the context of VR simulations. This gap also explains why there has been no research on *Presence* measurement while performing a maintenance task in a VR simulation before a disaster. Exploring this area can serve as a platform for further assessment of VR for training in safety awareness and prompt evacuations during emergencies while engaged in demanding occupational tasks. Moreover, research in this direction would also highlight the need for further VR studies regarding emergency preparedness and egress tenability at the factory conceptual stages.

The current study thus simulates a gas powerhouse for occupants to replace air filters on an engine and firstly evaluates the effects of a maintenance task on occupants' pre-movement time when a virtual fire emergency occurs. Additionally, we assessed the overall evacuation duration of occupants in the powerhouse simulation to understand whether the pre-movement delay subsequently affected the evacuation duration. Secondly, the research assesses *Presence* due to the maintenance task amidst the emergency evacuation to determine the level of *realism* experienced by the participants in the fire simulation due to the task. The research was conducted according to the virtual reality-based accident causation model (VR-ACM) to improve accidents' safety [10]. Therefore, we seek answers to the following research questions (RQ) to satisfy the aims of the experiment.

- RQ1: What is the effect of an engaging maintenance task on the pre-movement time in a powerhouse simulation when a virtual emergency fire occurs that necessitates evacuation in VR?
- RQ2: How does the maintenance task ahead of the evacuation increase the level of *Presence* experienced in the simulation?

The article is organized as follows to address our RQs. The following section presents the background, which elaborates on the related literature to the aims and objectives of the study. After that, the methodology describes the conceptual framework of the experiment, data collection, and analysis methods employed. The results section follows, which reports the obtained data in answer to our RQs. From there on, the discussion section follows with explanations of the results and the contributions and implications. Furthermore, the limitations and future works are also tackled in the discussion section. Finally, the study concludes in retrospect, emphasizing the importance of VR in assessing emergency fire evacuations at the plant conceptual stages.

2. Background

This section discusses the pertinent literature related to VR applications for fire evacuation and the concept of *Presence* in VR for reality evaluation in a VR experiment. Other parts of this section also relate to the pre-movement time of a facility and the evacuation duration during fire emergencies.

2.1. VR fire emergency evacuations

Advances in VR technology in mimicking real situations in virtual environments for real-time assessments and feedback have proven helpful for building skills during fire safety training, fire emergency evacuations, and emergency fire preparedness [10]. For example, while assessing human behavior during an emergency fire situation, Kinateder et al. (2014) emphasized the suitability of VR as a laboratory tool for improving fire safety, despite the ergonomic and technical limitations acknowledged in the research [22]. Similarly, while investigating the ecological validity of a VR experiment, Zou et al. (2017) establish that emotional valence and emotional arousal are necessary ingredients for determining the comprehensive level of the ecological validity of a VR evacuation experiment [20]. Furthermore, in a more comprehensive VR simulation, Shaw et al. (2019) investigated human behavior in an emergency fire scenario with the regular audio-visual VR devices compared to a multisensory condition incorporating thermal and olfactory senses [7]. The results revealed the significance of VR in fire emergencies with emphasis on the added benefit of multisensory virtual environments. In another study, Zhou et al. (2020) proposed a virtual environment for safety procedures (VESPRO) in a multi-semantic fire evacuation scenario that incorporates scene-related semantics besides the building geometrics [16]. Their simulation thus included the dynamics of the fire parameters, path accessibility, and path recognition for training. Kwegyir-Afful et al. (2021) echoed this in a VR fire accident causation experiment of a gas power plant (GPP) simulation for fire evacuation drills and fire mitigations and safety and ergonomics of the virtual environment. Their investigations revealed that a VR simulation environment could be ergonomically safe with negligible cyber sicknesses for safety assessment and fire emergency preparedness and response [2]. Other studies, for example, Wang et al. (2021) [17], analyzed the effects of several evacuation parameters in an underground commercial building and discovered that crowd congestion affects the evacuation duration when the number of evacuees increases by 50 [17]. Furthermore, Zhang et al. (2021) [18] also investigated the effects of route turning on evacuees during a fire emergency in VR. They detected that the turning angle during fire evacuation significantly affects evacuees' recognition and compliance to emergency signs [18]. VR evacuation simulations have also influenced changes to the design of emergency evacuation signs on buildings. For example, Tang et al. (2009) compared different types of emergency exit signage for evacuation duration and way-finding. They detected that the type of signs affects the period of way-finding during a fire emergency [23].

Few studies in VR have tacked the effects of a task before an emergency fire evacuation. For example, Cao et al. (2019) designed a VR study to examine participants' performance during a fire emergency. Their study incorporated the task of searching for the keys to a hidden treasure when a crisis ensued. As a way findings simulation, the results indicated that the experimental group who experienced the fire spent a long time finding the museum's exit than the control group who experienced no fire emergency [15]. Although their research is relevant, the emphasis was on the effects of the fire during the evacuation and not the treasure hunting task. This bolsters the earlier explained importance of the current study regarding the experimentation of an occupational task on evacuation before a fire emergency.

2.2. The concept of presence in a virtual environment

Telepresence, which is the shortcut for *Presence*, can be defined as the experience of being in a real environment even when one is in a virtual simulation [24]. The WS *Presence* questionnaire is usually cited in academic cycles for measuring the extent to which the simulation became the dominant reality in the virtual realm [19,21]. Kritikos et al. (2020) [21] modified and categorized the *Presence* questionnaire into four moderately related domains. These are interaction, visual aspects, subjective factors, and consistency with the natural world [21]. They investigated five elements in the virtual environment, and these made up the 21-item questionnaire which eliminated sound measurements since that was not a factor under consideration in their study. The current research adopted this version of the WS questionnaire with these factors: *Sensory fidelity, realism, involvement, control,* and the *distraction* factor as proposed by Kritikos et al. (2020) [21], which are explained as:

- *Sensory factor*: This factor measures the degree of movement in the VR environment that participants experience.
- *Realism factor*: *Realism* measures how close to reality participants perceive the scenes and structures in the VR environment.
- *Involvement quality factor*: This assesses the quality of the visual display and controllers on participants while performing the task and evacuation activities.
- *Control factor*: This factor measures the perception of participants' ability to control elements within the VR environment.
- *Distraction factor*: The distraction factor measures the ease of adaptation to the VR environment.

[21,24,25].

2.3. Fire evacuation preparedness

According to the FM *Global property loss prevention data sheets*, fire outbreaks in powerhouses costs an average of $24 million [26]. Despite these financial losses, the safety of those working in such facilities is paramount. Smoke from fires spreads quickly by reducing visibility, increasing the difficulty of finding the exit [27]. Furthermore, the natural gas that feeds the engines in powerhouses, being: Methane, 0.96%, Ethane 0.02%, and Nitrogen 0.02%, produces a highly explosive mixture [28]. These, in combination with compressed air, produce fires that power the engines to have electric power. Such a system can easily ignite and burn with devastating consequences. For example, six people lost their lives in a gas powerplant in 2010 at the Kleen Energy Systems Power Station, Connecticut, during a natural gas purging process [29]. Similarly, several people got injured with one casualty during a fire outbreak at the Mytishchi gas-fired power station near Moscow in 2019 [2]. To limit and prevent these occurrences, pre-movement duration assessments of gas powerplants during regular occupational tasks at the designing stages are necessary and bolsters the relevance of the current research.

2.4. Emergency evacuation timeline

Research indicates that estimating the means of emergency egress during fires in buildings plays a critical role in evacuation preparedness [2,6]. The emergency egress system performance of a facility uses two factors for evaluation. These are the available safe egress time (ASET) and the required safe egress time (RSET) [11,30]. The ASET is the maximum time between a fire outbreak until the conditions in the enclosed facility no longer become favorable for human occupancy. The RSET is the time interval between the ignition of fire until the occupants of the enclosed facility have completely evacuated [6]. The RSET comprises the detection time, premovement time and, traveling time of the most remote occupant of a building [9,30]. The fire detection time is the duration of the ignition of a fire until the triggering of the alarming devices installed within the premises. The pre-movement time is sometimes referred to as the pre-evacuation time [9,31]. The traveling (movement) time is the duration required for occupants of a building under threat to physically move and arrive at a place of safety [32]. The movement time depends on:

- The walking speed of occupants.
- The conditions of the occupants in the building during the fire.
- The number and width of fire exits/escape routes, and

- The location of the escape route.

2.5. Evaluating the pre-movement time

The pre-movement time in a performance-based fire evacuation design plays a salient role for safe evacuation during fire emergencies, for it is at this time when evacuees recognize the fire and respond appropriately and in time (Fig. 1). For this reason, the pre-movement time plays a crucial role in evacuation successes, especially during fires [27,32]. It constitutes; recognition of the fire emergency, decision to initiate evacuation or not, information to others or seeking further details of the hazard, and finally, the response time. According to research, the majority of the people who are adversely affected during fire emergencies are those who delay the pre-movement response time [27]. Fig. 1 below demonstrates the relationship of the pre-movement time in the emergency evacuation timeline.

3. Methods

3.1. Study design and experiment setup

This section explains the study design according to the conceptual model (Fig. 2), which relies on a modified version of Dhalmahapatra et al.'s (2020) VR-ACM [10]. As noted earlier, this model comprises 3D modeling and simulation, accident causation, and safety training. However, the current model substituted the safety training with evacuation drills while performing a specific task to investigate the effects on the pre-movement time during the evacuation. The tenability limits for safe evacuation from the powerhouse were:

- The minimum visibility during the evacuation was to be above 18 m, which is the maximum distance from the remotest location in the powerhouse to any of the four exits (Fig. 4).

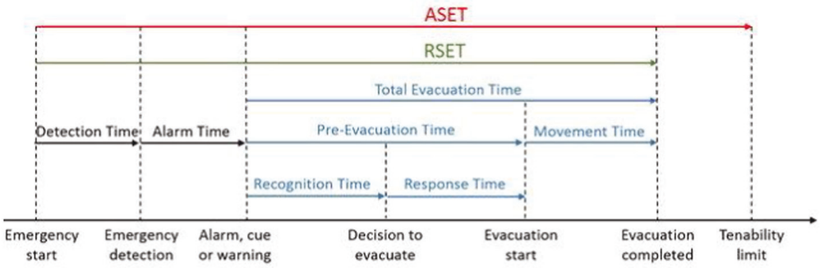
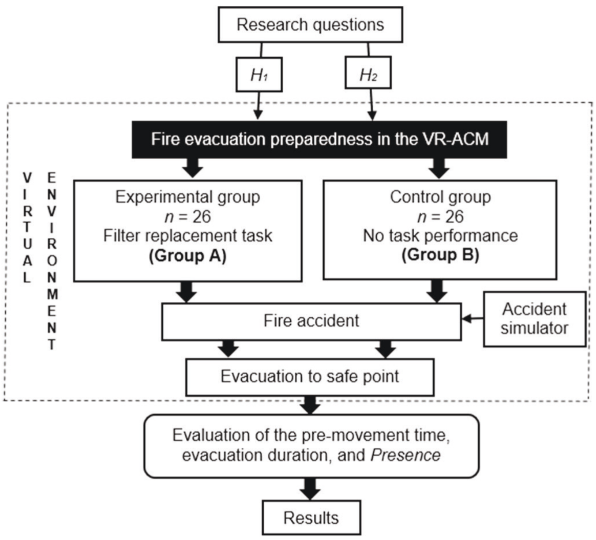


Fig. 1. The pre-movement time component of the evacuation timeline concept. *Cited from* Zhao et al. (2020) [33].



Note: H_n = Hypothesis
VR-ACM = virtual reality accident causation model

Fig. 2. The conceptual experiment model.

- The maximum exposure to carbon monoxide (CO) concentration was at 1200 parts per million (ppm) of air, the average for 5 min according to the British standard published document (BS PD) 7974–6:2019 [34], which prohibits worker exposure to any CO level above this limit.
- The air temperature tenable limit was not to exceed 60 °C according to the BS PD 7974–6:2019 guideline for the temperature limit that can endanger human life [34].

These criteria were factored as a time component by the accident simulator for occupants to egress before the fire effluents exceeded the limits for sustaining human life. During the fire, the simulator displayed these invisible quantities as smoke [35]. Primarily because most lethal gases such as toxic fumes and flammable gases do not possess optical properties. For this reason, they are represented with the smoke visualization technique to make it visible to participants by real-time data conversion as smoke. With the smoke traveling speed set at 1.0 [m/s] [21] and the progression speed of fire at 0.1 [m/s], the movement represented an actual fire hazard during the impending disaster. The experiment deliberately omitted gas alarms, fire sprinklers, and automatic sirens. The intention was to allow the occupants of the powerhouse in the simulation, who were participants of this study, to identify the hazard themselves and react accordingly by initiating evacuation.

The independent variable was the experimental intervention employing the filter replacement task by group A before the fire broke out. For group A, the accident simulator was designed to trigger while installing the new filter. According to the emergency evacuation plan, and in line with fire safety engineering principles [34], all participants were informed to evacuate the powerhouse through the closest exit the moment they saw the fire. Unknown to the participants, the fire simulator triggers the fire after 8 min into the immersion. The experimental, (group A) was engaged in the maintenance work while the control, (group B) was not tasked with any responsibility before the fire outbreak. Subsequently, we measured the pre-movement duration individually from the onset of the fire until the movement began towards the exit. Following this, we compared the pre-movement time of both groups to establish whether the task had any adverse effect on group A's recognition and response compared with group B to answer RQ1.

Furthermore, we compared the total evacuation duration between the groups from when the fire began until the occupant evacuated the building to the safe point. This comparison determined whether any differences noted at the pre-movement stage were transferred to the total evacuation duration. The final measurement was the perception of the levels of *Presence* experienced in the VR by both groups to answer RQ2, which was conducted with the WS *Presence* questionnaire. Furthermore, two hypotheses *H1* & *H2* were formulated to address RQ1 and RQ2, respectively. Fig. 2 displays these procedures based on the VR-ACM model.

3.1.1. Experiment location and instruments

The experiment was conducted at the Technobothnia virtual reality research center in Vaasa, Finland, between February 2019 and October 2020. This laboratory is equipped with state-of-the-art VR gadgets and computing power suitable for the current immersive assessment. The VR play area for participants' movement in the laboratory measures 3 m by 2.2 m. An HTC Vive VR head-mounted display (HMD) (China) with a 3D earpiece provided the display and audio for the virtual environment. Additionally, there were two hand-held controllers to offer interaction and intuitive response. Likewise, two sensors were positioned at two vertices of the laboratory to track movement through the headset and touch controllers while feeding the computer as occupants of the virtual powerhouse simulation. The powerhouse and fire effluents simulation was powered by a Windows 10 desktop computer (ASUS, Taiwan) with an intel core i7 dual-core processor running at 3.6 GHz. An NVIDIA GeForce GTX 1070 graphics card having a RAM of 32 GB enhanced the 3D simulations for the HMD. The model was built with the Fusion 360 version 2.0.9305 and the Unreal real-time game engine version 4.2, designing software for creating the simulations. Additionally, we monitored the actions of each participant who acted as an occupant in the powerhouse with the aid of a 64-inch flat-screen monitor (Fig. 3b).

3.1.2. Participants' selection

We recruited participants by emails and personal contacts in four universities in Vaasa, Finland. The inclusion criteria comprised university students with a minimum age of 20 years and without cognitive or motor limitations and normal or corrected-to-normal vision. A total of 52 participants, consisting of 11 (21.15%) women and 41 (78.85%) men with a mean age of 24.8 ± 6.1 years, were recruited for the experiment. This number of participants is per Gall et al.'s (1996) recommendation for the requirement of a minimum

Fig. 3. a. The powerhouse with the three engines. b. Immersion into the powerhouse simulation.

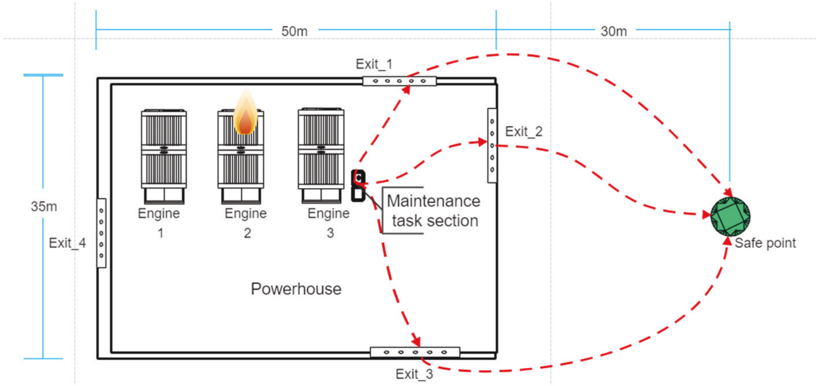


Fig. 4. The plan elevation of the powerhouse.

of 15 participants for an experiment, which Cohen et al. (2007:102) reiterate as the minimum number appropriate for an experimental group as well as in the control group for comparison [36,37]. Participants were randomly assigned to one of the two groups. Thence, the groupings are presumed to be fairly distributed to prevent any bias. Their educational pursuits at the time were as follows: First degree = 17 (32.7%), Master's degree = 26 (50%), and Ph.D. = 9 (17.3%). Participation was completely voluntary, and all the participants individually signed the informed consent form after receiving explanations of the experiment procedure.

3.1.3. Features of the powerhouse

The powerhouse is a conceptual rectangular single-story building design with a simple layout classified as B1 (Fig. 4) according to the BS PD 7974–6:2019 standard [11,34]. With a building space measuring 50 m long, 35 m wide, and 9.84 m high, the facility mainly contained three 16 MW gas-powered engines (Fig. 3a) that run on liquefied petroleum gas (LPG) and natural gas. An optimum lighting intensity of 400 lux was ensured in the vicinity according to the *American National Standard Practice for Industrial Lighting* (ANSI:1991) [38] for large-scale visual tasks. Having an exit on each of the four sides of the building with conspicuous signs that leads directly to the open space, the building design satisfies the exit requirements of the confederation of fire protection associations in Europe (CFPA E) [39]. This guideline is for fire safety engineering designs for evacuating safely from a building during emergencies [39].

3.2. Experiment procedure

Immersion into the powerhouse began when the participants individually wore the HMD headset and, with the controllers in hand, waited for the visual display of the interior of the powerhouse and gas-fired engines (Fig. 3b). The simulation presented every movement of the immersed person's head and hands in real-time according to a participant's line of sight and actions via the controllers. Interaction and control of equipment and machinery in the powerhouse occurred through this means. Navigation, controlling equipment, and walking in the simulation were possible by activating the controllers' assigned teleport and control buttons. As most of the participants lacked prior exposure to VR, we tested navigation in the simulation for a maximum of 10 min with the packing of cubes from the plant floor onto a trolley, as displayed in Fig. 5. The purpose of this initial exercise in the virtual realm was to enable both participating groups to become familiar with the VR gadgets for performing general tasks and evacuating from the powerhouse. The total exposure time in the immersion did not last more than 25 min, according to the HTC factory-recommended duration of fewer than 30 min per immersion with 10 min break if needed [40]. On average, the time for performing the entire experiment, including data collection from the questionnaire, lasted approximately 45 min for each participant of both groups.

3.3. The engaging air filter replacement task

Fig. 4 also demonstrates the location of the 3rd engine where the filter replacement task occurred. As aforementioned, the control group was not tasked with any responsibility, and they could freely explore and scrutinize the features of the powerhouse. Both groups were informed to evacuate through the closest exit (Fig. 4) to the safe point immediately after seeing the fire as previously directed in the emergency evacuation plan. Five phases (PH1 – PH5) were outlined for group A and four phases (PH1, PH2, PH4, and PH5) for group B, and these are explained as:

PH1: Familiarization of the features of the HMD and controllers for navigation and interaction in the simulation while immersed.

- Survey the plant to identify all exits and possible hazards.
- Move around the powerhouse and pack cubes from the floor onto a trolley in the plant. Fig. 5.

PH2: Adherence to the following emergency procedure regarding the evacuation:

- Stop all activities when a hazard is detected and move to the closest exit.
- Slide the door to open and evacuate.

Fig. 5. A participant parks cubes from the floor onto a trolley.

- Walk to the designated safe point outside the powerhouse (Fig. 4).

PH3: The preventive maintenance procedure for the air filter replacement task.

Each participant in group A received the explanation to the following procedure, which was also visually relayed to them sequentially as they performed each task in the simulation.

- Ensure that the engine is turned off.
- Push the trolley with the new filter close to the third engine, numbered 3
- Remove the filter cover and place it on the middle shelf of the trolley.
- Remove the old filter and place it on the lower shelf of the trolley.
- Pick up the new filter from the trolley and fix it in the air filter compartment of the engine.
- Pick up the filter compartment cover from the middle of the trolley and place it back to the engine.

Note: All the participants in group A were expected to identify the fire and initiate evacuation before completing this phase. As explained earlier, the accident simulator starts after 8 min into the task, and the premovement time and the time when each participant arrived at the safe point were measured in the simulation.

- PH4: Participants finally fill out the *Presence* questionnaire after the experiment.

3.4. Effects of a filter replacement task on the pre-movement time

In line with the perception that participants working on the task, group A, will not recognize the hazard early enough to initiate prompt evacuation as the control group B in the simulation, RQ1 was addressed related to this effect with the pre-movement time. Any significant differences between the mean results of the two groups answer RQ1. The first hypothesis therefore states:

- *H1:* An engaging maintenance task in a powerhouse simulation before a virtual fire outbreak adversely affects the pre-movement time in VR.

3.5. Analysis of the pre-movement time (H1)

To test *H1*, we analyzed the differences in the pre-movement time of the two groups by running the independent sample *t*-test between the mean of the associated populations. This was to evaluate whether a statistically significant difference existed between the results of both groups, as RQ1 sought to uncover.

3.5.1. Premovement time

In factories, warehouses, and plants, where the occupants are considered alert, awake, and aware of the workplace, the standard pre-movement time at the onset of fire is usually within 30–60 s [11,41]. This is consistent with the BS PD 7974–6:2019 standard, suggesting this duration for the first occupant within a scenario categorized “A”: *Awake and familiar* to the building [34]. Our VR-ACM eliminates alarms and expects the detection of the fire by the sight of smoke or fire. Therefore, we evaluated the recognition and response time that represent the pre-movement time of each participant from the time of the ignition of fire till movement towards the exit begun in the VR.

3.6. Effects of the filter replacement task on the level of presence

Both groups answered the WS questionnaire for assessing the *Presence* level experienced in the immersive environment (RQ2). The objective was to establish if a significant effect was evident on any of the five factors of the *Presence* questionnaire as afore explained. We thus posit *H2*.

- *H2:* An engaging maintenance task ahead of an emergency virtual fire evacuation in VR increases the experience of *Presence* in the simulation.

4. Results

This section presents the results of this study, which aimed to evaluate the effects of an engaging air filter replacement task on the pre-movement time during a fire accident that required early recognition towards evacuation. These results answer our RQs as stated in *H1 and H2.* To do this, we run the independent sample *t*-test in SPSS *v*26 to determine if a difference exists between the mean of the results of the two groups. However, we first analyzed the sample characteristics for normality.

4.1. Sample characteristics

According to Shapiro & Wilk (1965), the *t*-test parametric statistical method for evaluating the differences between the means of two groups requires that the dependent variables are approximately normally distributed for each category of the independent variables [42]. Thus, we first evaluated these by the z-values of the Skewness and Kurtosis scores for each group, tested to be between (−1.96 and + 1.96) [42] standard deviations for normal distribution in Table 1. Secondly, the data for both groups were skewed and kurtotic according to the eyeball test of the histogram (Appendix A and B) and the Q-Q plots (Appendix C and D). However, they do not differ significantly from normality as all the four z-values (Table 1) were within the specified range. Therefore, this holds the assumption that our data were approximately normally distributed [43].

4.2. The effect of the filter replacement task on the evacuation time

Table 2 presents the averages of the pre-movement time and the evacuation durations for both groups, the standard deviation, and the *p*-value to test if these differences are extreme. A mean pre-movement time of 60.12 s was recorded for the experimental (group A) while the control (group B) recorded 39.58 s which amounts to a 20.84-s difference between the two groups before initiating evacuation. Furthermore, the independent sample *t*-test was run to determine if this difference between the mean of the groups was statistically significant. The obtained value in the table was $t = 3.26$ and a *p*-value of .002 at a significant level of $p = .05$. Having a degree of freedom (*df*) at 25 for each group, the effect size, according to Cohen's *d* was measured at 0.905. Similarly, the table presents the mean evacuation duration of the control group, which resulted in 64.58 s, while that of the experimental group trailed behind at 82.42 s.

4.3. Presence and interactivity levels

This section presents the results of RQ2, which sought to investigate how the emergency evacuation during the maintenance task affected participants' perception of *Presence* in the VR environment as *H2* postulates. Table 3 presents these results according to the WS *Presence* questionnaire for groups A and group B. Accordingly, this table displays the mean, standard deviation, p-value, and t-values for the factors most affected by the maintenance task in the simulation.

Table 1
Distribution of variables.

Participants	Description	Statistics	Std. Error	z-values
Experimental group	Skewness	.896	.456	1.96
	Kurtosis	.376	.887	.42
Control group	Skewness	.584	.456	1.28
	Kurtosis	-.782	.887	.882

Table 2
Statistical differences in the pre-movement time and the total evacuation duration between the experimental (group A) and control (group B).

Groups	A ($n = 26$)		B ($n = 26$)		Δ (Sec)	Cohen's *d*	*t*	*df*	*p*
	M	*SD*	*M*	*SD*					
Pre-movement time	60.12	23.94	39.58	21.39	20.54	0.905	3.26	50	.002
Evacuation duration	82.42	18.01	64.58	18.34	17.84	0.982	3.54	50	.001

Table 3
Results of the *Presence* level of experimental (group A) and control (group B) in VR.

Factor	Group A		Group B		α = .05	*t*	*df*	95% CI
	M	SD	M	SD				
Sensory	5.92	0.43	5.79	0.42	P = .29	1.07	50	[-0.141, 0.306]
Realism	6.06	0.65	5.85	0.68	P = .26	1.15	50	[-0.158, 0.581]
Involvement	5.94	0.47	5.59	0.61	P = .03	2.30	50	[-0.044, 0.166]
Control	5.83	0.32	5.70	0.47	P = .25	1.17	50	[-0.093, 0.352]
Distraction	6.06	0.44	5.79	0.46	P = .04	2.16	50	[0.019, 0.519]

5. Discussions

This chapter explains the pre-movement time and the total evacuation duration results while participants were engaged in the task when the fire erupted in a VR simulation. Analysis of the *Presence* and *interactivity* levels experienced in the VR also follows. These results answer our RQs according to the experimental task (group A) and the control (group B). As explained earlier, the participants in group A performed the air filter task replacement by following visual instructions on a gas-powered engine. However, group B (control) was not engaged in any maintenance tasks in the simulation when the fire broke out. Both groups evacuated the powerhouse as soon as they detected the virtual fire triggered by an accident simulator. The simulator displayed the fire dynamics with the fire effluent as smoke for both groups of the experiment who acted as occupants of the powerhouse to initiate the necessary evacuation response.

5.1. The effect of the engaging maintenance task on the pre-movement time and evacuation duration

Referring to Table 2 at the results section, which addresses *H1* while answering RQ1, the mean pre-movement time of (M = 60.12, SD = 23.94) for the experimental group compared to that of the control group (M = 39.58, SD = 21.39) amounted to 51.89% difference, which is a substantial delay for the pre-movement time during a fire evacuation. From the independent sample t (50) = 3.26, and p = .002, which is less than 0.05, suggests that the intervention was statistically significant according to Cox (1966) [43]. Similarly, the effect size of 0.905 according to Cohen's d implies that this effect was substantial and supports our assertion in *H1*. For this reason, we can confidently affirm *H1*; that replacing the air filter in VR caused a substantial delay in the pre-movement time. Consequently, the experimental participants did not see the fire to evacuate as early as the control group. As participants were explicitly informed in the emergency evacuation plan (PH2 of section 3.3) before the experiment to stop working and evacuate the moment they saw a hazard, the noted delay was, therefore, largely a result of the lack of awareness due to the decline in the perception of other occurrences in the plant. On the other hand, the obtained mean evacuation duration results of the two groups (group A = 64.58 s) and group B (82.42 s) equally had a statistically significant difference measured at (t-test = 3.54, and p = .001). These differences also suggest a transfer of the pre-movement delay to the evacuation delay of the experimental group.

Besides, similar fire evacuation research findings in VR support these findings. For example, Cao et al. (2019) way-finding simulation while tasked with treasure hunting in a museum [15] and the experiment by Bourhim and Cherkaoui (2020) on pre-evacuation behavior during an emergency fire in VR, who compared their results with data from actual fire conditions [5]. Notwithstanding, it is necessary to compare the present study results to an actual powerhouse emergency fire drill consisting of a maintenance task with a similar work environment. Furthermore, due to the causes of some evacuation delays in real life, such as evacuees collecting personal items and making phone calls before initiating evacuation, as Bourhim and Cherkaoui (2020) explain [5], such a comparative study would be necessary to validate the experiment ecologically.

5.2. Presence and interactivity level analysis

According to the results presented in Table 3 in answer to RQ2, which sought to address the effects of the emergency evacuation during the maintenance tasks on participants' perception of *Presence* in the VR environment, the five factors of the *Presence* questionnaire produced mixed results. With the *control factor*, both the filter replacement task group and control group indicated high levels according to the 7-point scale (M = 5.83 SD = 0.32) and (M = 5.70, SD = 0.47) respectively. These values suggest that most participants experienced an appreciable level in controlling objects and machinery in the VR environment. Similarly, the values obtained for the *sensory factor* on the same scale for the task (M = 5.92, SD 0.43) and the control (M = 5.79, SD = 0.42) imply that both groups moved freely and thus perceived the VR environment and context to be rich and interactive. The *realism factor,* which represents how participants perceived the simulation to be real and meaningful, produced similar results (M = 6.06, SD = 0.65) and (M = 5.85, SD = 0.68) for the air filter experimental group and the control group, respectively. However, both the *involvement factor* and the *distraction factor* yielded significantly different results for the two groups. Particularly, these two factors represent how participants felt their *Presence* while immersed in the simulation and how close to reality they experienced the interaction within the virtual environment. In the *involvement factor*, whereas the experimental group scored (M = 5.94, SD = 0.47), the control group's score dropped convincingly (M = 5.59, SD = 0.61). Accordingly, these differences t (50) = 2.30, p = .03 are significant in line with the t-test at 95% confidence interval. Likewise, the results of the *distraction factor* (M = 6.06, SD = 0.44) for the experimental group and (M = 5.79, SD = 0.46) for the control group signals that the differences between the two groups t (50) = 2.16, p = .04 is also significant at 95% confidence interval. These variations are because, apart from the initial task of picking boxes from the floor and placing them on the trolley, and opening the door for evacuation as both groups experienced, the visual instructions coupled to the process of replacing the air filter caused a further engagement in the simulation. This is believed to result in the noted increase in the experimental groups' sense of *Presence.* Removing the filter cover and placing it on the trolley, picking the new filter from the trolley, and fixing it at the correct location on the engine before covering tended to reinforce a further sense of *interactivity* and *control* for the experimental group.

Consequently, this bolstered their sense of *involvement* and *distraction* according to the *Presence* measurement. We can thus conclude as *H2* postulates that the maintenance task in VR contributed to a higher level of *Presence*. The construct reliability of the *Presence* results was also satisfactory since the combined constructs exhibited a Cronbach's alpha of 0.716.

5.3. Contributions and implications

The current study's findings add to VR interactive fire safety drill research by demonstrating that participants can experience real-time emergency fire situations that necessitate evacuations in a controlled and safe virtual simulation environment. Besides, the immersive environment can be suitable for assessing the pre-movement time, which is vital for safe evacuation from a building.

- Generally, the study manifests the importance of exercising adequate levels of safety awareness while executing engaging tasks, especially in high-risk occupational settings such as in a gas-powered house.
- Specifically, the study demonstrates that captivating practices in a powerhouse simulation, such as engagement in a maintenance task, need to be undertaken with awareness of other occurrences like smoke in the vicinity that can endanger one's safety.
- The pre-movement time is an essential component during fire evacuations in VR since a delay at this stage is transferable to the entire evacuation delay, which is crucial during fire evacuations.
- Performing an engaging maintenance task in VR increases the *involvement and distraction* factors that represent the degree of *interactivity* and the sense of adaptation of participants according to the *presence* measurement, which is an essential ingredient for evaluating the degree of reality in a VR simulation.
- Although the evacuation speed in the immersive simulation may be synthetic, which is a general limitation of VR simulations [5], the study however holds immense significance at the pre-movement phase to which the merits of fire safety evacuations are exploited to further broaden VR utilization for realistic safety assessments. Other studies, for example, Cha et al. (2012) [35], Bhide, S. (2017) [4], Feng et al. (2018), and Kwegyir-Afful et al. (2021) [2], also performed similar fire evacuation simulations in VR, which validates the findings of the current study within VR research.

5.4. Limitations and future works

Despite this experiment's underlined contributions and benefits, the study encountered some limitations and constraints necessary for discussion, which also serves as the basis for further research in this direction. Firstly, the simulation did not consider a crowded fire accident evacuation situation that usually results in many casualties. This is mainly because our immersive VR setup could handle only one user at a time. Secondly, according to Ref. [22]Kinateder et al. (2014), social influence has been shown to affect evacuation decisions in VR [22]. Therefore, we hope to incorporate multiple users in the future for fire emergency drills simultaneously. Secondly, our setup consisted of only haptic feedback with audio-visual sensations for interactions in the simulation. In the future, we could incorporate a multisensory interface such as olfactory and thermal sensations to increase the level of *realism* in the virtual realm, as demonstrated by Shaw et al. (2019) [7].

Furthermore, the *Presence* measurement of the immersive encounter was recorded after the experiment, as the usual practice. However, the limitation of such post-immersive questionnaires is that they are subject to participants' memories. Since memories are also subject to individual retention capabilities, the consistency of the results can be affected. In the future, we hope to include questionnaires for answering while participants are immersed in the simulation. After the experiment, we also hope to conduct interviews to understand why some participants generally delay evacuating while engaged with similar maintenance tasks. Future interviews after the task-based evacuation could also ask whether participants wanted to complete the task before initiating evacuation. Lastly, this research also shares the same ecological validity issue, which all VR fire investigations, assessments, and training encounter due to the differences between actual fire situations and virtual simulations [5].

6. Conclusions

The study investigated the effect of an air filter replacement task on participants' responses during a virtual fire emergency that necessitated evacuation from a powerhouse simulation. Several records of the pre-movement duration and individual perceptions of the evacuation drill in the simulation environment were obtained as feedback from the participants who were immersed as occupants of the powerhouse. These participants were divided into two groups: the experimental (group A) and the control (group B). The experimental group was tasked to replace the air filters on a gas-powered engine during the fire eruption. The control group, however, was not assigned any responsibility during the fire. Both groups were to evacuate the powerhouse as soon as they recognized the hazard. The analysis of the mean pre-movement time for both groups realized that the experimental group significantly delayed recognizing the fire to initiate an early evacuation. Consequently, the results indicate a transfer of this delay to the evacuation duration of the experimental group. Moreover, the experimental group perceived the simulation environment to be more natural and interactive than the control, suggesting that the task added a higher sense of engagement that increased their level of *Presence*. The significant findings according to the hypotheses were highlighted as:

(a) An air filter replacement task in VR can affect the pre-movement time by causing substantial delays, which transcend further to minimize the evacuation duration in the VR simulation.

(b) Results of the *Presence* measurement generally imply that both participating groups experienced a high level of *realism* with the extra feeling of *interactivity* by the experimental group due to the maintenance task in the VR simulation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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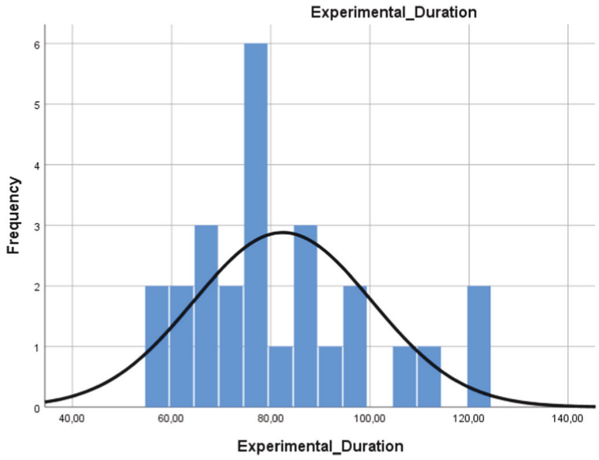
Appendices.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Frequency
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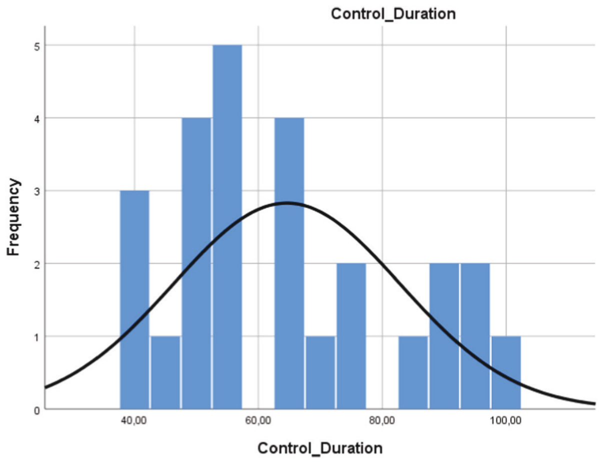
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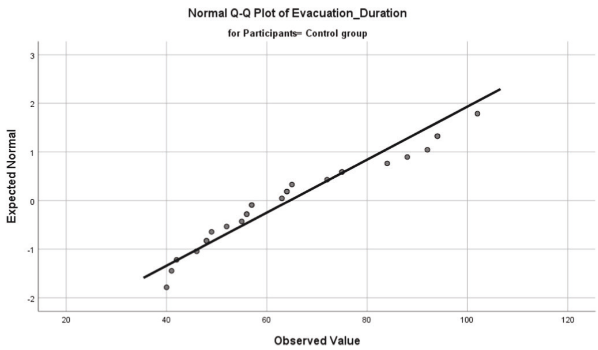
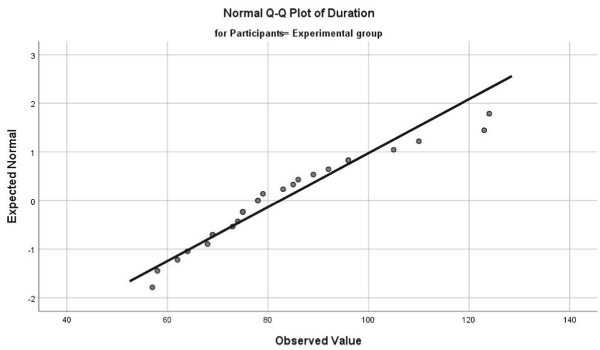

Normal Q-Q Plot of Evacuation_Duration
for Participants= Control group
Expected Normal
Observed Value



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Factory Layout Design and Optimization Focusing on Accident Prevention

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Abstract

Despite the growing interest in lithium-ion battery (LIB) applications worldwide, there is scanty research enhancing disaster reduction for improved safety and productivity at the factory conceptual stages. The current study aims to employ the digital factory concept in a LIB manufacturing simulation for process optimization while focusing on preventing accidents through fully immersive and interactive virtual reality (VR) technology. The realized simulation processes exhibit the dynamism of material flow and manufacturing processes for streamlining production to reduce or possibly prevent accidents. As the layout design of a facility plays a central role in the safety of operations, we conducted a job safety hazard identification and risk assessment (JSHIRA) procedure to curtail the hazards identified in the factory simulation. Consequently, the feedback loop of modelling with subsequent VR scrutiny for rectification produced a rigorously tested factory layout with several hazards identified and controlled/mitigated (t (31) = 6.79, and $p < .001$, at a confidence level of 95%) to indicate safety improvement in the final factory model. Similarly, a 4.51% improvement in production resulted from the optimization processes. Thus, the findings highlight the progress in the manufacturing layout of a 3D LIB simulation model and the control/mitigation of inherent risks by analyzing the dynamism of the processes in VR.

Keywords: Hazard risk assessment; 3D simulation; Virtual reality; Process optimization; Digital factory

1. Introduction

The rising demand for battery-powered solutions has accelerated growth in Lithium-Ion battery (LIB) manufacturing due to its high energy density, environmental friendliness, and long service life (Liu et al. 2021). With the EU gearing towards banning the manufacture of internal combustion engines (ICE) for automobiles by 2025, there is a growing expectation for LIB manufacturing (D'Souza, Patsavellas, and Salonitis 2020). Furthermore, a projected $129.3 billion LIB demand by 2027 has prompted a move toward improving the safety and efficiency of manufacturing processes in factory design (Berg & Vance, 2017; D'Souza et al., 2020; Mujber et al., 2004). On the same note, applications of traditional methods, such as throughput and resource utilization rates for ensuring disaster reduction, have proved to be minimally effective for improving designs while identifying hazards concurrently (Sekaran et al. 2021). VR also provides a platform for incorporating serious games in disaster prevention simulations, rendering it possible to increase participants intrerest while instituting adequate safety systems and devices in the factory (Ki 1999). Despite these benefits, researchers and practitioners encounter several challenges in designing factories for productivity while emphasizing accident risk reduction concurrently (Karagiannakis et al. 2022). Secondly, existing academic literature trails behind a comprehensive manufacturing design simulation utilizing productivity and accident prevention. Besides, the few studies tackling the subject present sectored results and fail to provide details necessary for a thorough analysis (Markwart et al. 2019). These compelling reasons call for a real-time design synergy between 3D-motion simulations and VR during factory designs.

Meanwhile, research suggests that a manufacturing system's performance, reliability, and functionality can be increased by improving the safety of the production processes (Feng et al., 2022). In like manner, Guo et al. (2018) emphasize that workplace safety increase's reliability and productivity. Additionally, digital manufacturing enables the integration of employee safety as a top priority while designing machines and production processes to reduce accidents (Plinta and Krajčovič 2015; Michalos et al. 2018). Although some organizations silently attribute productivity and safety as mutually exclusive when promoting efficiency with increased safety regulations and procedures. Feng et al. (2022) explain that the contrary is rather beneficial, emphasizing the difficulty of staying productive in a harmful and accident-prone atmosphere. Similarly, Coulibaly et al. (2008) demonstrate that the essential ingredient for improving product availability is increased productivity, maintainability, and safety in industries such as aeronautics and automotive. Their research further expresses the need to blend these parameters for evaluation during the facility design. Katsuro et al. (2010) also discovered the impact of safety and health policy adherence on worker productivity, stressing that workers' enthusiasm significantly reduces serious accidents and unsafe working conditions. As the duration of one's work in a hazardous working environment increases, their physical health and fitness are also affected, resulting in decreased performance (Zhu and Li 2021) Besides, Dobrescu et al. (2019) reiterate that investing time and resources to preventing accidents at the factory conceptual stages is more prudent than spending vast amounts of money on modifications of an existing structure, legal battles, insurance premiums and medical bills because of injuries and fatalities.

Furthermore, restoring a company's poor health and safety image can be an irreversible loss if tainted due to rampant man-made disasters. Despite these advances and high safety standards in LIBs manufacturing, several incidents suggest the need to concurrently consider productivity optimization and safety concerns while designing LIB factories. This is essential because LIB manufacturing is inherently hazardous, and accidents are usually severe with catastrophic events, including human casualties. For example, a fire at the Dahongmen LIB factory, Beijing, on 16th April 2021 resulted in the death of two firefighters and several degrees of injuries. Before this incident, a fire occurred in 2014 at another LIB factory in Dongguan, China, causing five fatalities and six injuries (Rosewater and Williams 2015).

Considering the gaps and the need mentioned above, this study primarily aims to incorporate VR for modelling and simulating factory processes with accident prevention initiatives at the factory in the design to promote a serene working environment that supports both paradigms. Overall, the optimization process minimizes travelling times and waiting times while identifying possible hazards by assessing the associated risks at each workstation for the necessary risk control/mitigation. We thus formulated the following research questions to address these questions (RQs).

- RQ1: How much improvement can be realized by applying VR for designing and optimizing a LIB manufacturing process simulation?
- RQ2: What type of work-related hazards regarding the severity and likelihood of occurrence can be identified and categorized according to the estimation of the underlying risk factor on a risk score?
- RQ3: Which of the identified work-related hazards can be eliminated when a Job safety hazard identification and risk assessment (JSHIRA) procedure is applied to a 3D factory process simulation model?

The article is structured as follows to address these RQs: Firstly, we review the manufacturing of LIBs in conjunction with literature on process design simulations in VR. Secondly, we present an overview of digital factory applications in manufacturing designs. Subsequently, we elaborate on the study methodology and design, including 3D-motion simulations with visualizations of the factory model in VR. The hypotheses are also presented here. The final section presents the study results, discussions of the findings, limitations, interpretations, manufacturing process optimization, the JSHIRA process for disaster reduction, and the generalizability of the results. We hope the findings will promote greater collaboration between industrial practice and academia to improve manufacturing process designs, ensuring optimum safety.

2. Background

Manufacturers increasingly exploit several digital tools to streamline and accelerate production throughput (Markwart et al. 2019) Designing a manufacturing facility with equipment and functions as an integrated model with safety concerns requires several factors and parameters like planning the factory layout, line balancing, hazard risk assessments, control and mitigation, emergency preparedness and response (EPR) and factory process design improvement (Kuhn, 2006; Mujber et al., 2004; Kwegyir-Afful et al., 2021). Meanwhile, simultaneously evaluating human performance and safety in industrial systems has been a demanding engineering topic utilizing digital tools for effective process design(Peruzzini et al. 2021).

2.1 Lithium-Ion battery manufacturing processes

Cylindrical LIB manufacturing entails five core stages. These are:

- Electrode production.
- Cell assembly.
- Formation and cell sealing.
- Model assembly
- Testing and battery pack assembly (Blomgren 2016).

Manufacturing begins by mixing solvents to coat the copper and aluminium foils, which constitute the anode and cathode (Heimes et al. 2018; Nitta et al. 2015). The calendaring, drying, and slitting processes are performed separately for the anode and cathode electrodes before rolling together while sandwiched with insulation material (Blomgren 2016; Turetskyy et al. 2020). Next is spot welding of terminals, vacuuming, and electrolyte filling (Väyrynen and Salminen 2012; Omogbai and Salonitis 2016; D'Souza, Patsavellas, and Salonitis 2020). Subsequently, the formation cycling, which constitutes the charge/discharge operation and ageing processes, follows. Ageing is the most time-consuming procedure and often the main bottleneck in LIB manufacturing (Shukla and Kumar 2008).

2.2 Digital Manufacturing Concept

Digital manufacturing employs several tools for analyzing systems while evaluating different scenarios necessary for optimal decision-making (Chouchane et al. 2019; Guo et al. 2018). According to research, the salient purpose of digital manufacturing is to provide an integrated platform for visualizing details of manufacturing processes and products virtually before actual implementation (Jahangirian et al. 2010; Banga et al. 2021). These measures are necessary for identifying hazards, preventing delays, and avoiding empty running and unnecessary processes caused by inefficient manufacturing layout designs (Kuhn 2006; Sekaran et al. 2021). Furthermore, 3D modelling and motion simulations enable dynamisms for revealing potential wastes; thus, the technology is employed to discover inherent factory design flaws (Choi, Jung, and do Noh 2015;

Huang et al. 2021). Consequently, utilizing these tools increases the efficiency of a manufacturing design by minimizing the time for handling work between processes

For this reason, applying the digital factory concept promotes efficient disaster scenario for adequate analysis (Ruggiero et al. 2021)These features of the digital factory promote the utilization for factory disaster assessments (GUNDRAN et al. 2021). For example, Jinasena et al. (2021) developed a digital LIB manufacturing model for determining the energy and material requirements in a manufacturing process and throughputs. Results of their study indicate that the digital manufacturing process can minimize energy usage. In another study, Gundran et al. (2021) integrated VR for enhancing casualty disaster management in a simulation training program . The outcome concludes VR's capability to communicate design parameters to customers before commencing the actual construction.

2.3 Factory process design improvement

Factory process design for improvements includes factory floor planning, process streamlining, quality assurance, and inventory management (Wendler 2012). Simulating a factory design for improvement targets the layout functionality and the intended factory processes (Mujber, Szecsi, and Hashmi 2004; Kwegyir-Afful 2021). Implementing these methods relies on adequate in-depth assessment and analysis of the production flow (Kwegyir-Afful 2021) . This underpins the significance of VR utilization to provide real-time 3D-motion perceptions for identifying bottlenecks while minimizing processing time during the factory design.

2.4 VR factory design focusing on accident prevention

Although most of the research in factory process optimization does not concurrently include the human factor, some research works utilizing digital manufacturing are considering this jointly. For example, Malik et al.'s (2019) research focuses on using VR to develop a unified framework for integrating human-robot simulation with VR. The simulation, run as an event-driven simulation, helped evaluate human-robot interaction, human-robot cycle times, the safety of working with the robots, optimizing the layout, and programming robot control (Malik, Masood, and Bilberg 2020). Similarly, Peruzzini et al. (2021) employed VR technology for designing a manufacturing process simulation, considering the associated ergonomic implications for workers by duplicating what could occur on the shop floor. According to the results, the VR methodology proved to be more suitable for detecting operator comfort angles and appropriate in predicting *critical* processes for improving the factory layout design. Implications of the study are that users of the technology immersed in the factory simulation can be directly involved as workers through immersive virtual simulations to identify potential hazards, assess task feasibility and interaction quality in terms of perceived comfort, and improve disaster reduction (Qie & Rong, 2022). This can reform workstation design and task planning to reduce inefficiencies (Peruzzini et al. 2021). In another development, Ko et al. (2021) designed a process and accident interactive simulation utilizing an augmented virtual reality-based platform in training for enhanced communication between control room operators and field operators while preventing accidents in the factory. Despite these developments, the gap in hazard risk assessment during factory manufacturing and optimization processes utilizing the digital manufacturing concept remains.

A process or workplace can be evaluated for possible disasters in various ways, and each method has advantages and disadvantages (Altan et al., 2022). For instance, the worker-focused Job Hazard Analysis (JHA), which examines each task a worker must complete and safety indicators that may be helpful to reduce risk, is highly effective at safeguarding workers (Gundran et al., 2022). However, a broader hazard analysis method may be required if there is the need to evaluate a complex system rather than the safety requirements of individual workers. OSHA provides several typical techniques for identifying possible risks in these systems, including FMEA, which is a methodical, proactive strategy for assessing a process to determine potential failures in the system as well as to gauge the relative impact of the various failures to pinpoint the areas of the process that require the most remarkable improvement (Weidinger, J. 2022).

2.4.1 Job safety hazard identification and risk assessment (JSHIRA)

The Job safety analysis (JSA) method is a safety and health process that enables individuals and organizations to integrate accepted safety and health principles and practices into their work (Getuli et al. 2020). Four processes take place during a JSA procedure. These are:

- Job selection for analysis.
- Job division into sequent of events.
- Identification of inherent hazards.
- Evaluation of hazard mitigation measures.

The JSHIRA procedure in Fig. 4 in the method section incorporates both JSA, and hazards identification and risk assessment (HIRA) methodology for evaluating hazards associated with performing tasks on a 5x5 risk matrix in Fig. 1. The Matrix is used for assessing the severity of a risk occurring and the probability that it would happen (Hegade, Rajkumar, and Murthy 2017). The severity of a risk score is a quantitative method for determining the impact of a hazard on a risk scale. Getuli et al. (2020) simulated a computer 3D factory model and conducted a HIRA in an existing manufacturing facility and a VR simulation. Their study indicated no significant differences in the number of hazards and risks identified in both cases. This signifies the possibility of conducting a risk assessment procedure on a 3D manufacturing facility in VR during factory design as Qie & Rong (2022) postulate. Therefore, a JSHIRA procedure in VR incorporates experiences of hazards related to a job in a safe environment to analyze the consequences and prevent their possible occurrence in real life. Rajkumar et al. (2021) employed the JSHIRA safety management procedure in 20 different work processes at a ferrous foundry and identified several hazards that required mitigation. This approach identified 50% of the work-associated hazards (Rajkumar et al. 2021). However, their work did not incorporate the needed rectification of the dangers to justify the proof of concept. Thus, signifying the need for the investigation of the application of JSHIRA method in a simulation where the hazards can be visualized in a three-dimensional factory simulation for implementing the necessary rectifications.

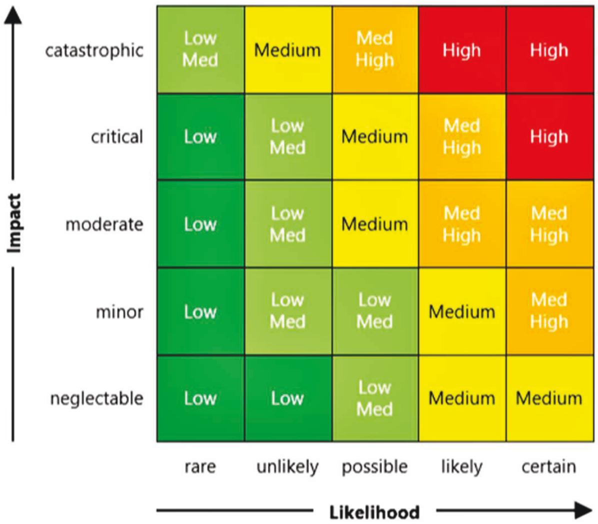

Fig. 1: A 5x5 Risk matrix *cited from* (Maziah Munirah et al., 2019)

3. Study methodology

The study's main objective was to design and optimize the manufacturing processes of a 1GWh LIB factory in VR while ensuring that the created model offers a safe working environment by reducing potential sources of man-made disasters. We first evaluated the total manufacturing parameters and durations per batch to meet the targeted demand for achieving this objective. Further duration reduction without compromising workplace safety in the simulation was the basis for implementing process optimization and the hazard risk assessment procedure in this study. These objectives are sectored below to match the three research questions in the introduction section and the subsequent hypotheses:

- Design and optimize a 3D-motion factory model incorporating the processes and dynamisms for manufacturing LIBs. The process optimization follows by analyzing the manufacturing sequence in the simulation to reduce possible bottlenecks and inefficiencies. The first hypothesis (*H1*) is designed to address RQ1, which sought to quantify the improvement that could be achieved in the factory through this process. *H1* postulates: A manufacturing layout design can be optimized by utilizing a fully immersive VR process simulation.

- Analyze details of the created factory model in VR to assess work-related hazards and categorize these according to a risk score in answer to RQ2. The second hypothesis (*H2*) thus states: Several work-related hazards in the factory process simulation can be identified and categorized according to the estimation of the underlying risk factor on a risk score.
- Conduct a JSHIRA process to mitigate potential hazards inherent in the factory model, targeted at RQ3. The third hypothesis (*H3*) states: Specific work-related hazards can be identified, assessed, and significantly reduced, controlled, or eliminated when a JSHIRA procedure is applied to a 3D factory process simulation model.

The study follows the conceptual framework in Fig. 2 for creating the factory and assessing the layout, related hazards, and disasters for the necessary rectifications. This framework was implemented through modelling, simulation, and evaluating the factory's required production durations with the subsequent hazard risk assessment. We further determined the most suitable layout of the factory based on the processes for manufacturing LIBs. Thus, the research design was mixed with qualitative and quantitative methods, which sought objective information from the immersed participants to improve the layout model while assessing possible inherent hazards. This dual approach was necessary to ensure that the final design would realize a safe and efficient model that would not require further modifications in the actual factory, according to Galbusera et al. (2022).

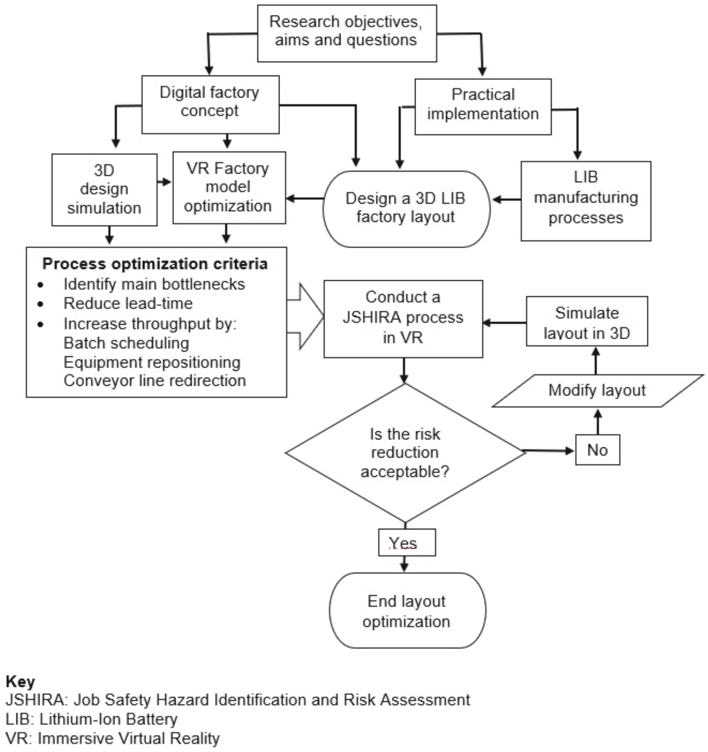

Fig. 2: Research conceptual framework

3.1 Software and system specification

A 32 GB RAM Windows 10 computer (Asus, Taiwan) having a core i7-7700 quad-core processor with a GTX 1070 graphics card powered the factory simulation in VR. Our utilization of VR for scrutinizing the factory layout is due to the technology's immersive and interactivity features essential for factory design improvement and the JSHIRA procedure. Immersion was with the aid of the HMD, two base stations, and handheld controllers (HTC Vive, China). The factory model was constructed with the Visual Components (VC) 3D manufacturing simulation software version 4.0. With the assistance of SketchUp version 4.2.1 and Fusion 360 3D-motion designing software, we modelled all equipment unavailable in the VC library. We then exported these models to the 3D world of VC for rendering with the necessary equipment dynamisms based on the specifications for the intended manufacturing processes.

3.2 Factory layout design

The digital factory model began by constructing the factory floor and walls from the VC library to the 3D world. Following this, we considered several layout alternatives, and the most appropriate design for our intended manufacturing sequence was the U-shaped design (Fig. 3A). The reason is that a U-shaped factory design allows proximity between stations, flow continuity, flexibility, and control of production. For this reason, the factory building is designed rectangular (Fig. 3A). It measures 52 meters by 21 meters to conform to Ramakrishnan & Nallusamy's (2017) research, which suggests that production flow harmonizes and balances well with previous and subsequent workstations in a U-shaped manufacturing design.

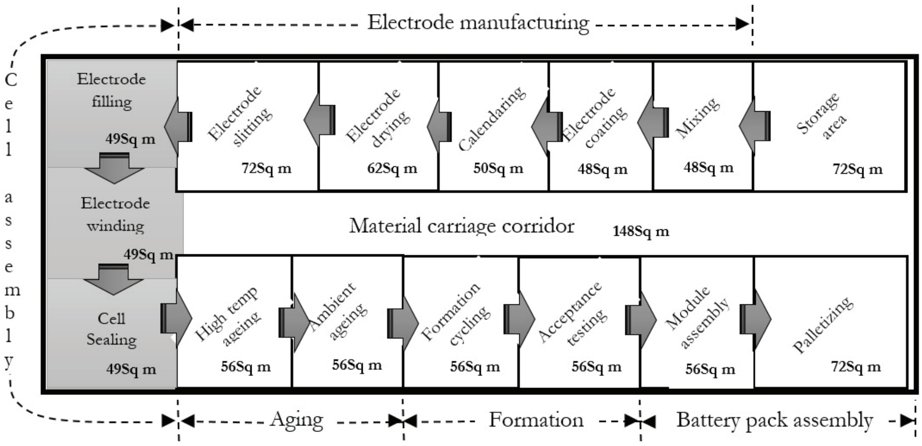

Fig. 3A: LIB factory plan

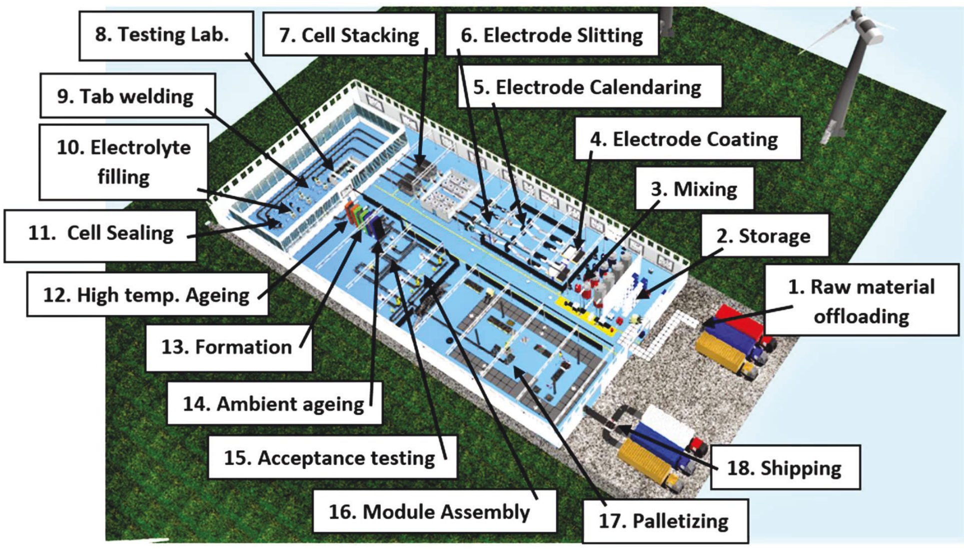

Fig. 3B: LIB factory model

3.2.1 Simulating the LIB factory

Following the construction of the factory floor, ceiling and walls in VC, the process simulation began with the material storage area and the electrode manufacturing processes (Fig. 3B). The electrode manufacturing process involves mixing the slurries for the anode and cathode materials, coating, calendaring, and slitting the aluminium and copper electrodes with the required solvents. Both electrodes (positive and negative) are wound together with an insulator. Filling the cell cup with an electrolyte precedes the formation process, which conditions the cell by charging, retaining, and high-temperature ageing. We then simulated the cell assembly workstation, constituting the cell case and cover production for electrode insertion, welding, electrolyte filling, cap welding, and degassing. Fig. 3B pictures the factory simulation illustrating the various machines. Relevant to the process tasks at each stage are scheduling jobs, routing, and allocation of materials.

3.3 Layout optimization and evaluation criteria

The main impetus for the optimization was identifying process bottlenecks at each workstation by reducing the lead times and travelling distances. The objective was to minimize the throughput time at all the workstations. Corrections were carried out akin to our conceptual framework for the optimization Fig. 2. The purpose was to seek the most suitable machine/stage proximity to yield the lowest cycle time yet not jeopardize workers' safety at each stage. Since cycle time is inversely proportional to throughput, decreasing the cycle time was the target in increasing the throughput. The improvement followed a cycle of design, simulation in 3D, evaluation in VR, and modify the layout if needed (Fig. 2). The final assessment was hazard risk reduction (detailed in section 3.5). This cycle continued at all the workstations until all avenues for possible improvement were covered. The process targeted reducing non-value-adding activities such as waiting, conveying, and queuing. According to Michalos et al. (2018), implementing these measures simplifies a layout as a crucial ingredient for efficient designs.

As mentioned earlier, immersion in VR provided 3D motion visibility for understanding the operations of machines and general workflow in the factory. This process provided suggestions regarding design flaws and bottlenecks in the model for possible improvement. After that, the layout optimization process continued by instituting corrective measures to shorten the travelling distances of conveyor lines while eliminating operational bottlenecks in the factory model. These measures were implemented to evaluate *H1*. Eight stakeholders were individually immersed in the factory model to analyze the processes and provide feedback for the necessary optimization. These stakeholders constituted a process and production engineer and two factory managers from the project company. Others were a researcher, two university professors and two university students.

3.5 The JSHIRA assessment

While identifying bottlenecks in the factory layout to improve the production sequence, we also conducted a JSHIRA in the factory layout to firstly identify work-related hazards to satisfy *H2*. According to Hegade et al. (2017), one of the most *critical* components for ensuring workplace safety is identifying potential hazards related to the working environment for each task to be performed in the factory. For this reason, it was necessary to identify specific work processes at each processing stage while improving the factory layout. The JSHIRA procedure combines two safety methods. The first is the JSA method, a safety tool employed predominantly to define and control factory processes, jobs, or practices, as mentioned in section 2.4.1. The other is the HIRA process which is also used in identifying and assessing hazards associated with the working environment and work processes with the subsequent implementation of relevant control measures to mitigate the identified threats. Therefore, the JSHIRA process constituted a factory walk through all the manufacturing stages to identify hazards to address *H3*. Visible hazards at any of the production stages were identified and quantified according to the severity of the hazard and the probability of occurrence.

3.5.1 Participants for the JSHIRA procedure

Regarding this process, 15 university students with a year minimum of work experience undertook the JSHIRA procedure and hazard control/mitigation (Table 3). Participation was voluntary, and participants signed an informed consent form before the fully immersive experiment. Since our VR setup could accommodate only one user per immersion, the JSHIRA procedure was designed with a user evaluation method to discover hidden issues necessary for promoting the accident prevention initiative. Each participant assessed possible hazards related to the work process and environment as workers at the workstation.

Fig. 4: The JSHIRA method. *Cited* from (Rajkumar et al., 2021)

3.5.2 Implementing the JSA in the factory simulation

The JSA, as Fig. 4 demonstrates, began by walking through the ails at each workstation of the factory simulation while analyzing the specific tasks, activities, processes, equipment, and the general working environment. First, we elaborated on the duties at each workstation required in the factory to the participants. This was to enable them to perceive and analyze the related hazards more intuitively.

3.5.3 Hazard Identification and Risk assessment

Following the JSA, the hazard identification in was conducted by the participants monitoring and assessing the work environment in the simulation for possible static hazards within the simulation facility. Secondly, the potential risks arising from work practices and processes such as collision with a moving forklift, cut from the slitting machine, or crashing during electrode calendaring and falling objects from the shelves were evaluated. According to the HIRA procedure, all the hazards identified were tabulated before quantitatively categorizing the risks according to the severity (consequence) and probability (likelihood) of occurrence (Table 3, in the Results section). Subsequently, we determined the risk score by multiplying the mean of the severity by the mean of the probability of the accident to represent the impact of the risk for prioritizing the mitigatory action. According to the calculated risk score, particular attention was placed on any activity with risk within the *critical* and *catastrophic* range of Table 1. On this scale (Table 1), the risks were ranked and scored according to *Equation* (*1*).

Risk score (R) = Severity (S) X Probability (P) (*1*)

This risk score corresponds to the 5x5 risk matrix (Fig.1), with 1 being the risk category with the lowest impact and 25 the highest risk. The mitigatory hazard measures were subsequently taken after the categorization to eliminate or decrease any identified hazards to acceptable levels. Assessments were made to ensure that the mitigatory steps did not instead introduce new hazards. Table 3 in the *results and discussion* section provides the mean results of the participants for each identified risk.

The means (M) of the processes before and after the optimization were compared through a t-test to evaluate the significance at the 95% confidence level of the VR intervention. This was necessary to test the statistical difference between the safety of the factory before and after the immersive JSHIRA procedure

Table 1. Risk score categorization, description, and control/mitigation requirements

Risk category		**Risk score**	**Description (Priority)**	**Action required**
Severity	**Likelihood**			
Negligible	Rare	1 – 4	Very low	No action is required
Minor	Unlikely	5 – 8	Marginal	Caution notice
Moderate	Possible	9 – 14	Medium	Moderate impact
Critical	Likely	15 – 19	High	Major change needed
Catastrophic	Certain	20 – 25	Very high	Immediate correction

4. Results and discussions of findings

This section provides the results according to our hypotheses related to designing and optimizing the LIB factory in VR for subsequent JSHIRA processes to ensure optimum process safety in the plant. We firstly evaluated the total throughput time per batch as explained in section 3 with data from Heimes et al. (2018), Jinasena et al. (2021), and Liu et al. (2021) to be within 2184.28 minutes (Table 2).

4.1 Production duration and batch sizes

In answer to RQ1 related to the improvement obtainable in the design through the immersive optimization process, Table 2 below compares the evaluated minimum manufacturing demand results, initial throughput times after the 3D simulation and the final throughput times (optimized) after several modifications to the design. The process offered several views, such as Fig. 5 and 6, to *critically* analyze material flow, resource capabilities, and risk assessment. This resulted in fully utilizing tangible resources to enhance manufacturing efficiency and reveal hazards for mitigation. Moreover, the simulated values in the Table were obtained after setting up the layout in 3D. The optimized values represent the quantities obtained after the VR factory walk and improvement procedure. Secondly, the immersive factory walks provided the necessary visibility for improving the factory layout by identifying inefficiencies in the flow of materials. The simulation recorded the processing durations as the parts entered a processing stage and exited. Table 2 displays the following three categories to evaluate *H1*:

- The calculated minimum customer demand for manufacturing the cells,
- The initial simulation results, and
- The optimized manufacturing values after the VR factory walk and assessment.

Table 2. Manufacturing throughput time at the five works stations

Manufacturing throughput time (min)	Electrode production	Cell assembly	Formation cycling	Model assembly	Palletizing and wrapping	Throughput ∑
Min. demand	134.60	75.10	1925.92	32.9	15.76	2184.28
Simulated	136.47	76.48	1915.24	34.40	15.76	2178.35
Optimized	102.33	56.76	1877.01	33.95	14.23	2084.28
Δ	34.14	19.72	38.23	0.45	1.53	94.07
∑ Δ%	33.36	34.74	2.04	1.33	10.75	4.51

4.2 Design analysis

The total increase of 4.51% achieved in the throughput time in Table 2 occurred mainly by altering the production batch sizes and repositioning machines to shorten transportation distances between stages and from one processing machine to the other. This difference in throughput time is substantial especially considering the cumulative effect in subsequent cycles per annum, suggesting that there can be a significant improvement in a manufacturing process simulation design when it is subject to critical VR scrutiny to answer RQ1. This was performed by adjusting subsequent manufacturing stages such that the inputs were nearest to the outputs of prior stages according to acceptable safety limits of factory machine placements. Consequently, placing equipment at each stage sequentially and in the closest proximity reduced the travelling distances and conveying times since a shortened conveyor line produces a faster production flow, directly affecting the throughput rates. Furthermore, it was to cause all operations in the line to occur within the specified time frame to prevent starving or waste and avoid costly errors. Likewise, we eliminated the non-value-adding activities by standardizing the processes and balancing the workflow. This ensured smooth continuous material flow, which was implemented following the proposal by Turetskyy et al. (2020). Performing this exercise facilitated the flow of materials for processing to ensure continuity, timeliness, and efficiency. Consequently, analyzing the production through VR enabled us to identify potential bottlenecks to reduce inter-process inventory and unnecessary manufacturing bureaucracies. Essentially, these modifications for optimization were instituted while considering the suggestions of the JSHIRA processes.

4.3 Streamlining the manufacturing processes

While changing equipment positions within each processing stage, alterations to the design configuration were performed simultaneously to facilitate production at each workstation and within related stages of production. This method minimized movements within the factory and ensured smooth flow of materials and cells from one location to the other, as captured in the model assembly section in Fig. 6. However, in our attempt to eliminate the waste at each workstation, we initially realized that we were just shifting the waiting times to other workstations. Consequently, this caused inventory to pile up at the different workstations while removing bottlenecks at the cell and battery module assembly stations. However, we resolved this issue by reducing the batch size (Fig. 6) while targeting the continuous flow of materials and battery parts. The results in Table 2 also demonstrate that both Shendarkar et al. (2008) and Berg (2021) explain that 3D simulations alone do not provide the interactivity and dynamism necessary to assess the requirements for improving process designs. Indeed, adjusting the entire system has increased the manufacturing rate of the layout, as the results at the individual workstations provided in Table 2 indicate.

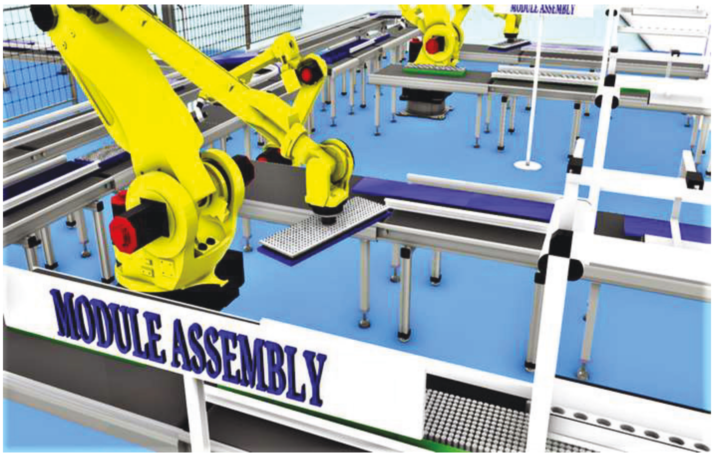

Fig. 5: Articulated robot at the cell assembly workstation

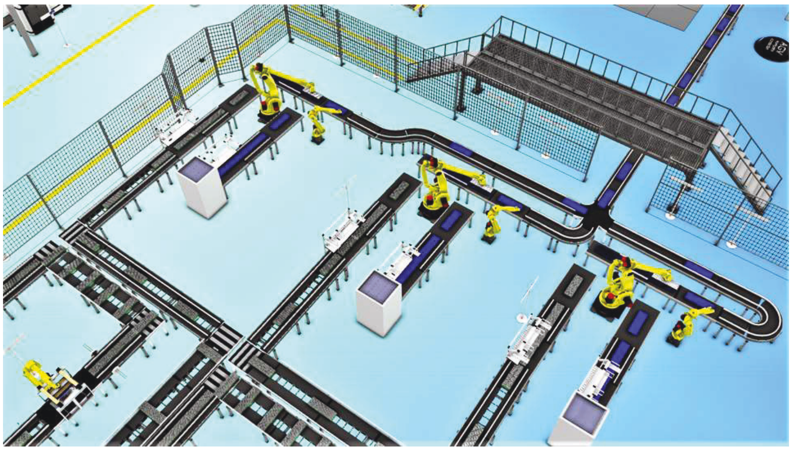

Fig. 6: Cell model assembly

We further balanced the line by assigning tasks with the required lot size to the various workstations in such a manner as to minimize waiting times. Several times, this was repeated until the processing durations were synchronized with the primary workstations' respective capacities. These included reducing batch waiting times, cell inspection times, conveying times, and queuing times. Thirdly, the layout configuration minimized movements within the factory and ensured that materials and products moved smoothly and in time from one workstation to the next. The advantage was in ensuring that the completed model efficiently handled production demands. By understanding the implications of reducing bottlenecks and balancing the line after several iterations through VR, our final layout improvement of 4.51% in the first production cycle answers *H1* in the affirmative.

4.4 Results of the JSHIRA procedure

4.4.1 Identification and categorization of the identified hazards

Table 3 provides the risk score in answer to RQ2 regarding the work-related hazards that could be identified and categorized in terms of the severity and likelihood for control/mitigation. Furthermore, the types of work-related hazards discovered were also elaborated in the Table in answer to RQ2 as postulated by H2. These were executed according to the severity of the risk score categorized as; *negligible, low, medium, high,* or *catastrophic* in Table 1. Through this process, we could identify and mitigate static and dynamic activities in the factory that could potentially cause harm. We initially considered all hazardous scenarios regardless of the possibility of their occurrence. This process ensured that the work procedures, equipment position, and dynamism did not pose any hazards that could cause harm while working or during emergency evacuations. According to the risk matrix, if an identified risk was higher than the benefit, then appropriate actions were taken to avoid the hazard. It was also realized that the nature of the specific task and the conditions at each workstation determined the related hazards and risks present at the workstation.

Table 3. Results of the JSHIRA

Identified hazards	s	p	r	Action taken to mitigate risk	S	P	R
Electrode production							
Electrolyte falls from shelves	4	3	12	Provide guards	4	2	8
Electrolyte (corrosive) spillage	3	5	15	Provide exhaust fume on outlets	2	2	4
Fire hazard of electrolyte material	5	3	15	Increase automation in handling	5	1	5
Forklift crash (loading/offloading)	5	4	20	Replaced forklift with AGV	2	1	2
Projectile injury during slitting	4	4	16	Provide machine guards	4	2	8
Trips, slips & falls: Same level	3	3	9	Provide slip-resistant floors	3	2	6
Fire during heat drying, calendaring & vacuum drying	4	3	12	Fumes extractor system, enclosure for machines	4	1	4
Radiation during laser drying	5	4	20	Radiation shield/add distance	5	2	10
Fire during laser drying	5	1	5	Provide a vacuum environment	4	1	4
Noise from electrolyte filling	2	4	8	Enclosed environment	1	3	3
Cell assembly							
Finger caught in electrode rolling machines	5	4	20	Provide fail save system with machine safeguards	4	2	8
Crash with robotic arm	4	5	20	Provide barricades / sensors	1	2	2
Fumes during welding of tabs	3	5	15	Ensure air circulatory system	3	2	6
Noise: Electrode insertion	2	4	8	Seal in vacuum chamber	2	3	6
Radiation from laser welding	4	4	16	Radiation-shielded with distance	4	1	4
Trips, slips & falls: Same level	4	2	8	Provide slip-resistant floors	2	1	2
Formation cycling							
Electric shock	5	3	15	Barricades/locked electric panels	1	2	2
Fires during aging	4	3	12	Increase safety distance	4	2	8
Fall on conveyor belt	5	4	20	Install safeguards	5	1	5

Fumes from chemical reactions	4	4	16	Install extractor system	4	2	8
Palletizing and wrapping							
Crash with robotic arm	5	4	20	Install machine safeguards	5	1	5
Crash with forklift	5	4	20	Mark designated paths	3	1	3
Trips, slips & falls: Same level	4	3	12	Provide slip-resistant floors	4	2	8
Carriageway							
Emergency exits too narrow	4	4	16	Widen exits to standard	3	2	6
Extinguishers: Wrong position	3	3	9	Well positioned	3	2	6
Few emergencies exit signage	3	3	9	More signs added	2	2	4
Trips, slips & falls: Same level	3	3	9	Provide slip-resistant floors	3	2	6
Forklift accident	5	5	25	Provide AGV/define walkways	1	2	2
Falling from height	5	4	20	Increase barricade height	5	1	5
Storage area							
Flammable materials on shelves	5	3	15	Provide airtight containers	5	2	10
Raw material falling from shelves	4	3	12	Protective guards/ lighting	4	2	8
Forklift crash (loading/offloading)	5	4	20	Provide enough signals/training	5	3	15

Note AGV = autonomous guided vehicle, p = probability before risk assessment, P = probability after risk mitigation, r = risk score before risk mitigation, R = risk score after risk mitigation, s = severity before risk assessment, S = severity after risk mitigation.

4.4.2 Elimination of work-related hazards

This section explains the hazards that could be eliminated, controlled, or reduced when the JSHIRA was employed to evaluate *H3*. From the mean results of the risk assessment in Table 3, the highest risk realized before the mitigation was a forklift accident at the carriageway. According to the risk score, this was considered catastrophic with a high priority at 25 points. To mitigate this concern, we substituted the forklift with an autonomous guided vehicle (AGV) for transporting materials on the carriageway. This change reduced the risk factor to 2, at 92% risk reduction, implying negligible risks. Based on this procedure, ten catastrophic risks and 9 critically high-risk activities with ratings (20 – 25) and (15 – 19) points respectively on the risk score were noted in the initial layout. Similarly, control measures were instituted for the moderate (9-14) and minor (5 – 8) ranges, respectively, having 9 and 4 risks. Table 3 also provides the various safety measures instituted, which addressed most of the hazards to the marginal and minor ratings according to the risk category scale. However, the two risks could not be reduced to appreciable levels. These were the forklift crash during loading/offloading at the storage area (risk ratings 20) and possible radiation hazards (16) during laser drying at the cell assembly section. Therefore, we suggest adequate safety training, constant maintenance of forklifts, and instituting safety procedures for loading/offloading and personal protective equipment. Subsequently, these risks were reduced to 15 and 4 correspondingly. Regarding the risks in the moderate risk category (9 – 14), nine hazards were recorded and reduced with the corresponding measures described in the Table. These measures saw most of the risks in this category reduced to the *marginal* and *negligible* range, resulting in a 27.08% risk reduction to the minor risk range (5 – 8) on the risk score, according to Table 1. Eight risks were also reported in the marginal/minor risk category, and these were equally mitigated to achieve a 24.13% further risk reduction.

The overall results from the paired sample *t*-test in testing the hypothesis under observation (*H3*), indicated a statistically significant difference before (M = 14.7, SD = 5) and after (M = 7.8, SD = 3.6) the JSHIRA intervention at $t\,(31) = 6.79$, and $p < .001$. These values therefore suggest that the results are significant at $p < .05$ according to Shapiro and Wilk (1965), which also affirms *H3*.

4.5 Limitations

The primary limitations encountered during the factory simulation, optimization and hazard risk assessments are the absence of the following critical factors: Labor requirements, material costs, and details of workers' essential role in the production processes. Secondly, we did not consider the stochastic effects of the breakdown of machines and the absence of the overall cost structure with energy consumption on the choice of appliances. Thirdly, no assessment was made on the weather effects (ambient temperature and humidity) on dry rooms, a factor that affects the duration of electrode production in real-life instances. Fourthly, the design excluded financial implications for choosing machines and equipment.

In the JSHIRA procedure, the most significant limitation was identifying hazards by non-experts. However, since safety, health and environment (SHE) experts do not exclusively conduct industrial hazard risk assessments, we are convinced that most identified hazards were viable. We also experienced frequent freezing of the computers due to the numerous activities that were run simultaneously in the simulation. For this reason, some simulations were run separately, and the results fused into the setup. Similarly, the simulation did not address details like the safety features of the cell and battery model, explosion-proof containers, heat-sealed diaphragm and mass automation to limit human errors. However, the study provides a real-time manufacturing process environment for optimizing and rectifying specific factory hazards.

Regardless of the layout being modelled with data and specifications from actual LIB manufacturing equipment and machinery, given the limitations above, the development of this model only serves as a demonstrative design for improvement with proactive work-safety purposes. It does not, therefore, deliver accurate data for LIB manufacturing. We acknowledge these limitations, which require consideration in interpreting the study results. However, these limitations do not jeopardize the research findings highlighting VR's impact while modelling 3D-motion manufacturing simulations for process improvement focusing on preventing accidents.

4.6 Directions for future research

Future studies in this VR for process optimization and accident risk reduction can include financial estimates for choice of equipment, the energy consumption of the setup and weather effects, labour requirements, evacuation possibilities, and ergonomics of the work environment. Such studies can also address the limitations of frequent computer freezes with state-of-the-art computing power and head-mounted display (HMD) technologies having enhanced rotational and position tracking features. Furthermore, studies can expand to include SHE experts in the JSHIRA procedure to ensure a higher level of professionalism.

4.7 Research implications and contributions

Notably, the factory model combines theoretically anchored real-time simulation principles and manufacturing procedures for designing and analyzing details of a LIB manufacturing factory layout, considering the factory's safety by preventing accidents. This is especially timely given the growing interest in VR technologies and battery-powered solutions. The findings generally imply that designing the machinery and processes of a factory in 3D-motion simulation and verifying through VR has benefits in offering better visual perception and comprehension of the process for design optimization. A vital aspect of the manufacturing processes needed in a factory has been simulated and evaluated for optimization and safety evaluation. Such measures allow real-time visualization of the effects on production in the process design before implementation.

The current study addresses the gaps identified earlier in the literature by the following contributions.

- Firstly, the research contributes to the limited research in the discipline that utilizes the digital factory concept for manufacturing process improvement. The study demonstrated this by the significant production throughput achieved through critical scrutiny while immersed in the factory simulation.
- Secondly, by applying VR to improve manufacturing safety, the study contributes to the literature with a JSHIRA procedure for addressing the inherent hazards in the factory design.
- Thirdly, our study is one of the first to consider combining a JSHIRA procedure with factory design and optimization to promote productivity and prevent accidents in the factory process simulation model.
- Next, the fourth contribution is an essential antecedent of VR for hazard mitigation in a factory design. By employing process simulations in 3D, the study revealed salient details of hazards for the necessary control/mitigation.

5. Conclusions

The study sought to design and prevent accidents in a digital 3D factory simulation model in VR. The simulation comprises the building, equipment dynamism, and manufacturing processes for producing LIBs. Details of the processes constitute raw material offloading through production at the various workstations to the finished product ready for shipment. Issues addressed in the simulation that improved the design are identifying the bottlenecks evident in the waiting times and scheduling for the correct allocation of materials and parts, ultimately enhancing the throughput. Essentially, the immersive factory walks enabled a JSHIRA, which proactively investigated and helped institute adequate measures for promoting workers' safety while streamlining the manufacturing processes for the necessary corrections. The result of the study is an optimized factory simulation layout that has been thoroughly analyzed and scrutinized by addressing inherent errors and flaws. Consequently, this amounted to a significant improvement in the throughput in answer to RQ1 regarding the improvement obtainable in the design through immersive optimization.

On the other hand, the JSHIRA procedure also identified several hazards in answer to RQ2 in the factory that was subsequently categorized and ranked into five divisions according to the 5x5 risk matrix. Following the control/mitigation process instituted for eliminating and reducing the noted hazards, most of the previously ranked *critical* and *catastrophic* hazards were rectified and re-evaluated to be between the *negligible* and *marginal* range to answer RQ3.

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