Development of Interactive and Distributed Virtual Environments for Immersive Communication in the Furniture, Fixture and Equipment Sector

ABHINESH PRABHAKARAN

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Declaration

This thesis has not been submitted in substance for any other degree or award at any university or place of learning, nor is it being submitted concurrently in candidature for any other degree or other awards. I confirm that the work's intellectual content results from my own independent work/investigation and efforts and no other person's.

Abhinesh Prabhakaran

Acknowledgements

"Everything you want is on the other side of fear"

-Jack Canfield

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Dedications

This thesis is dedicated to my parents, wife, and my brother for their love, trust and support that have guided and encouraged me throughout my life. A special dedication to my boy, Aryan; your smiles make life worth living and helped me unwind, whenever I needed a break from my research.

Abstract

Despite the significance of the furniture fixture and equipment (FFE) sector to the UK's economy and the construction industry, this sector faces challenges that impede its productivity and performance, including an inability to meet end-user expectations in the delivery of its services. Lack of adoption of digitalisation and poor design communication between the stakeholders have been identified as one of the issues leading to challenges in the FFE Sector. In this context, visual representation offered by virtual reality (VR) can play a critical role in communicating the designs with the stakeholders effectively. However, evidence suggests that the current state of the VR application in the FFE sector lacks three critical advancements namely BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (multi-user interaction). Therefore, the aim of this study was to bridge this gap through the development and testing of novel virtual environments for immersive communication between FFE and its construction project stakeholders. Furthermore, pre-conditions for the successful implementation of the developed VR applications were evaluated in this study through experimentation.

A sequential, exploratory, mixed-method research design was adopted for this study in three phases. In phase one, an extensive literature investigation was carried out to acquire deeper knowledge of existing literature to understand the state-of-the-art developments of immersive technologies in the construction industry with a specific focus on the current challenges and benefits of implementing immersive technology. Phase two of the study involved the development and testing of immersive, distributed and interactive VR applications for various scenarios of the FFE communications for construction. Each application was developed by applying rapid application development methodologies and combining BIM, game engine and low latency cloud server development paradigm. The developments were tested through quasi-experiments and evaluation by stakeholders to ascertain usefulness and utility in the FFE sector context. The first development focused on interactive VR for FFE and was tested among (n = 12) stakeholders using a quasi-experiment in a single-group, pre-test-post-test design. The second development focused on distributed immersion for FFE design communication and was tested among construction stakeholders involved in FFE design decision-making (n = 26). The distributed VR application was further tested further among (n = 9) stakeholders in the context of FFE retail and showcasing of FFE products. The experimental approaches in the second phase adopted combined quantitative and qualitative evaluations to ascertain system usability which fed into further development and finetuning of applications. Finally, in the third phase of the study, the interactive and distributed VR applications were validated among wider group of construction stakeholders (n = 117) using a survey to ascertain industry-wide utility and usefulness as well as establish factors that influence their wider adoption in the sector. A combination of descriptive and inferential statistics was applied to establish findings including Kruskal-Wallis and ANOVA to measure variations in views across different segments of the population of respondents.

Findings indicated that the interactive distributed immersive virtual FFE environment can enhance the productivity of the design team through a collaborative virtual workspace offering a

synchronised networked design testing and review platform. Furthermore, it can reduce the time required for the stakeholders (Client/end-user, architect, FFE designer/contractor, FFE manufacturer) to comprehend and test the design options. In addition, the developed VR applications can enhance the design communication and quality of the design and encourage a collaborative culture in the industry and improve the design satisfaction of the stakeholders. It was also identified that the VR applications developed for this study can reduce the time required for design decision-making significantly when compared with traditional methods. In the retail and product showcasing context, the system was found to be a highly efficient and viable tool, which can deliver a compelling and richer experience similar to an FFE in-store experience. The testing also revealed that the proposed system not only improves the sense of presence but also brings in a new dimension of a sense of being together, which has a positive impact on decision making. Cumulative findings of this study revealed that distributed and interactive VR has become essential to digitalising the FFE sector's design communication, with improved design communication being regarded as the most important benefit of its use. Conversely, the most critical challenge that inhibits the implementation of these two VR applications in the FFE sector is the perceived cost. This research proposes a step-change in the way furniture design is communicated and coordinated through an immersive virtual experience, thus allowing informed decisions making and creating shared understanding before the commencement of the construction activity.

Keywords: *Immersive technology, Virtual reality, Furniture, Interior design, Architecture, engineering and construction, Challenges, Benefits, distributed virtual reality, Interactivity, Immersive communication, Co-Presence, Usability, Intention to adopt, Virtual showroom, Collaboration*

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List of Abbreviations

FFE	Furniture Fixture and Equipment
AEC	Architecture Engineering and Construction
BIM	Building Information Modelling
IFC	Industry Foundation Class
NBS	National Building Specifications
ImT	Immersive Technology
VR	Virtual Reality
VE	Virtual Environment
CAVE	Cave Automatic Virtual Environment
AR	Augmented Reality
MR	Mixed Reality
DVSE	Distributed Virtual Shopping Environment
COFFEE	Collaborative Furniture Fixture and Equipment Environment
SPSS	Statistical Package for the Social Sciences
GDP	Gross Domestic Product
A and C	Architecture and Construction
CWAS	Construction Works and Associated Services
2/3D	Two/Three Dimension
IVE	Immersive Virtual Environment
ICT	Information and Communication Technology
RAD	Rapid Application Development

CAD	Computer Aided Design
FBX	Film Box
HMD	Head Mounted Display
ROI	Return on Investment
SME	Small and Medium Enterprise
SD	Standard Deviation
TAM	Technology Acceptance Model
V/E-Commerce	Virtual/Electronics Commerce
SUS	System Usability Scale
ITC-SOPI	The Independent Television Commission Sense of Presence Inventory

List of Publications

❖ Forms chapters of this thesis

[1]. **Prabhakaran, A.**, Mahamadu, A., Mahdjoubi, L., and Booth, C. A. (2022-Accepted). Understanding the Benefits of Immersive Technology Use in the Furniture Fixture and Equipment Sector: A Systematic Review, *Proceedings of the Sustainable Ecological Engineering Design for Society (SEEDS)*. **[Chapter 2]**

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[3]. **Prabhakaran, A.,** Mahamadu, A. M., Mahdjoubi, L., Manu, P., Che Ibrahim, C. K. I., and Aigbavboa, C. O. (2021). The effectiveness of interactive virtual reality for furniture, fixture and equipment design communication: an empirical study. *Engineering, Construction and Architectural Management*, *28(5)*, 1440-1467. https://doi.org/10.1108/ecam-04-2020-0235 **[Chapter 4]**

[4]. **Prabhakaran, A.,** Mahamadu, A., Mahdjoubi, L., and Boguslawski, P. (2022). BIM-based immersive collaborative environment for furniture, fixture and equipment design. *Automation in Construction***,** 142**,** https://doi.org/10.1016/j.autcon.2022.104489**.** **[Chapter 5]**

[5]. **Prabhakaran, A.**, Mahamadu, A., Mahdjoubi, L., and Booth, C. A. (2022 in press). Towards development of a distributed virtual furniture, fixture and equipment shopping environment. Springer, Cham. **[Chapter 6]**

[6]. **Prabhakaran, A**., Mahamadu, A., Mahdjoubi, L., Booth, C. A., and Aigbavboa, C. (2022). Virtual reality utility and usefulness in the furniture fixture and equipment sector: A validation of interactive and distributed immersion. *Smart and Sustainable Built Environment*, https://doi.org/10.1108/SASBE-02-2022-0038 . **[Chapter 7]**

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Chapter 1: Overview of the study

1.1. Background

Furniture, fixture, and equipment (FFE) is a critical segment of the construction industry and is considered to be the single greatest determiner of a building's day-to-day functionality and could conceivably influence the architectural aspects of the facility (Workspace, 2017). The importance of FFE to a facility cannot be over-emphasised considering the fact that occupants spend 90% of their time indoors (Ergan *et al.*, 2019). This emphasises the significance of FFE and its effective arrangements in influencing human experience within a built space, which demands a collective decision-making environment. Apart from the human experience and well-being within a built space, the FFE sector has a great impact on the economy as well. The FFE sector alone in the UK was estimated to have contributed approximately £12.5 billion to GDP for the year 2016 with a 4.8% increase in 2017, employing more than 3,390,00 people, and remains one of the most critical segments of the UK's construction supply chain (The British Furniture Confederation, 2018).

Despite these impressive statistics, the FFE sector, similar to any other sector in construction, faces challenges that impede its productivity and performance, including an inability to meet user expectations for the delivery of their services (AMA Research, 2014; Rend *et al.*, 2014; The British Furniture Confederation, 2018). Lack of digitalisation has been identified as one of the issues leading to the challenges of the FFE. Furthermore, poor stakeholder communication between the FFE sector, its designers and, on the other hand, project architects, contractors, clients and facility users lead to misaligned expectations which further exacerbate misunderstanding of design intent and expectations, thereby contributing to project failure as a result of the dissatisfaction. One of the ways in which communications can be improved is through the adoption of digital ways of working, including digital collaboration and communication. However, the sector still relies on traditional methods when collaborating with other construction project stakeholders.

The productivity and performance of the FFE sector are heavily dependent on effective design communication and collaboration with its stakeholders (Oh *et al*., 2004, 2008; Wang and Wang, 2008; Yoon *et al*., 2010). However, since the seminal work by Schön (1988), it has been widely acknowledged that the end-user/client and designers occupy an entirely different design world, making design communication and coordination extremely inefficient. Council and Spillinger (2000) noted that effective design communication can improve the quality of a project and ultimately reduce the cost and time over-runs. Gallaher *et al*. (2004) and Portman *et al*. (2015) noted that inefficient design communication, resulting from information asymmetry, cognitive differences and selection difficulties among the stakeholders, can result in a wastage of 30% of the total value of a given project. This can have a huge impact on the FFE sector, as this sector mostly operates on a low-profit margin and tight schedules (Oh *et al*., 2004; Prabhakaran *et al*., 2021).

FFE is one of those products that are often purchased for appeal and functionality. Several empirical studies (Forsyth *et al*., 1999; Pakarinen and Asikainen, 2001; Kotler and Armstrong, 2003; Kozak *et al*., 2004; Yu *et al*., 2021) have concluded that the design of an individual piece of FFE, as well as how well it blends with the architectural aspects, has a profound influence on the stakeholder's design decision. Also, various studies have revealed that aesthetics plays a major role in the design choice of FFE elements (Creusen and Schoormans, 2005). Additionally, due to the significant expense and long product life cycle of FFE, stakeholders must make difficult trade-off decisions with regard to critical factors such as style and functionality (Oh *et al*., 2004).

Therefore, the decision-making behaviour in FFE is a complex process involving the consideration of constraints such as cost, space availability, and matching with the architectural aspects of the facility (Oh *et al*., 2004). Thus, the result of such a complex decision-making process is the uncertainty arising among the stakeholders over whether they have made the correct design choice (Oh *et al*., 2004). Hall and Tewdwr-Jones (2010) and Yu *et al*., (2021) reported that one of the greatest reasons for such uncertainties is the stakeholders' inability to visualise and test various FFE combinations in the context of the space in which they want to use them. Considering the fact that 70% of the information processing leading to a design decision is through our visual senses, it is inevitable that the stakeholders need to have additional tools to visualise and interact with the design to communicate the design effectively (Heilig, 1992; Chirico *et al*., 2018).

In this context, visual representation and interactivity offered by virtual reality (VR) can play a critical role in effectively communicating the designs with the stakeholders, as observed by Roy and Tai (2003) and Yoon *et al*. (2010). The role of visualisation and interactivity in decision-making has been emphasised and explored by many researchers. Yoon (2010) used a web-based VR system to understand the decision-making behaviour in FFE. Despite the system being an exploratory VR, the findings of the study revealed that VR-based systems can assist decision-making considerably. Similarly, a study by Oh *et al.* (2008), using a web-based VR and conventional formats of two-dimensional design, affirmed the finding of Yoon (2010). In all these studies, it was concluded undoubtedly that visualisation using the aid of virtual reality technology in understanding how well an FFE element blends with the architectural space and how well it serves the function of that space has a great impact on the stakeholders' design decision.

1.2. FFE sector in the UK

There are some ambiguities in the definition of FFE. In accountancy terms, FFE is defined as “movable furniture, fixture and equipment that have no permanent connection to the structure of a building or utilities” (NBS, 2010). However, in property law in the UK, a “fixture” is considered to be a set of fixed assets which is attached to the building, so it forms a part of that building (Gerald and Kathleen, 2013). NBS (2010) defines FFE based on the Common Arrangement of Work Section (CWAS) with a better consistency of the terminology which states that “furniture is an item that is free-standing or hung by screws, nails and hooks and fixture is any item that is intended to be reasonably permanent and is affixed to a property through the application of plaster, cement, bolt, screws, nuts or nails”. For this study, the NBS (2010) definition of FFE was adopted in view of its encapsulation and better consistency of the terminologies. In the UK, the FFE sector forms part of both the construction supply chain and the retail industry, thus belonging to a wide spectrum of the market (Zenner *et al*., 2020). Moreover, the construction stakeholders also form part of the FFE’s retail segment depending on the size of the project. Construction stakeholders, therefore, engage with FFE retail and marketing when selecting different products to incorporate into the design,

The FFE sector in the UK exists in a dynamic environment consisting of several stakeholders who communicate constantly with each other during different phases of a construction project. The stakeholders of the FFE sector typically involve the client or end-user, FFE designers, FFE contractors, FFE manufacturer/supplier, architects and interior designers. The FFE sector is a critical segment of the construction industry and remains the single greatest determinant of a building’s day-to-day functionality, which could conceivably influence the architectural aspects of a facility (Yu *et al*., 2021). The FFE plays a significant role in any facility, which can constitute approximately 12% to 16% of the construction budget and sometimes 40% (the healthcare industry has the highest budget for FFE products) of the overall construction budget (Fryer, 2012; Zhang *et al*., 2021). Similarly, the relevance of the retail segment of FFE cannot be also over-emphasised, considering the contribution it makes to the UK's GDP (£12.5 billion), and the number of jobs it creates in the UK (3 390 000) (The British Furniture Confederation, 2018). Thus, both segments of the FFE sector are value drivers that must not be under-estimated (Fryer, 2012; Zhang *et al*., 2021). The methods (e.g., 2D plans, sketches, brochures) used for communicating the designs with the stakeholders in both segments of FFE are more or less the same; hence the term "FFE sector" in this thesis is used to represent both construction and retail segments.

1.3. Current approaches to communication in the FFE sector

As mentioned earlier in section 1.2, the FFE sector exists in a dynamic environment consisting of several stakeholders (Client/end-user, architect, FFE designer/contractor, FFE manufacturer) who communicate constantly with each other during different phases of a project. Cheng *et al*. (2001) define communication as "the transformation of resources such as information, knowledge, data and skills among the stakeholders using shared symbols and media". For any construction project to be successful, effective communication is a fundamental factor (Cheng *et al*., 2001; Zhang and El-Diraby, 2012; Wen and Gheisari, 2020; Zhang *et al*., 2021). In the FFE sector, the most common communication with construction project stakeholders often relates to the design of the products, their incorporation into the design of the facility, as well as product selection. A typical workflow of design communication in the FFE sector is still structured as a sequential chain of activities in which each activity is separated in time and space in a "relay race" where design information pertaining to the spatial and technical information is communicated with stakeholders, using conventional methods such as two-dimensional (2D) paper and digital formats of floor plans, sketches, brochures and catalogues (The British Furniture Confederation, 2018) together with regular meetings to communicate designs through problem identification and information exchange (Gautier *et al*., 2008). However, (Bowden *et al*., 2004; Dadi *et al*., 2014; Chalhoub and Ayer, 2018; Du *et al*., 2018; Shi *et al*., 2020) suggested that this mode of design communication is highly inefficient as a result of the “noises” that can occur during encoding and decoding of the information. This process of encoding and decoding information essentially describes the well-published theory of the linear standard communication process (Dadi *et al*., 2014). In the literature about construction communication, poor design communication resulting from errors made in the interpretation or decoding of the message has been identified as the most frequent cause of a decline in productivity (Eckert and Boujut, 2003). Moloney and Harvey (2004) noted that design communication based on 2D methods is reductive, analytical and incapable of conveying the subjective aspects of designs. Dai *et al*. (2009) affirmed this and concluded that 32% of the negative productivity in the FFE sector is the result of inaccurate and poor information delivery. Further, Hall and Tewdwr-Jones (2010) noted that poor presentation and the inability to visualise the information are the two major reasons for poor design communication. Egan and Latham (1998) reported further that organisations following traditional methods of design communication do not provide a solid foundation for an effective construction process. They also stressed that the prevailing methods of design communication (based on 2D paper and digital) are not effective, especially when the stakeholders involved lack technical skills.

In a bid to address these issues caused by conventional design communication methods, the FFE sector has recently embraced building information modelling (BIM) to communicate data-rich design with its stakeholders (Cotey, 2017). The introduction of BIM into the FFE design workflow has enabled the placing of furniture and documenting and scheduling of the inventory to be more systematic and easier (Johnston, 2011). While BIM can offer several benefits to the FFE sector, Chalhoub and Ayer (2018) suggested that, even though the use of BIM has increased, the method of communicating design still relies on 2D interfaces to communicate data-rich, 3D BIM models. Dunston *et al*., (2011) and Wen and Gheisari (2020) affirmed this argument and noted that this method of design communication is inefficient, as modern-day construction projects are becoming increasingly complex. Paes *et al*. (2021) showed that the 3D designs conveyed over 2D interfaces are incapable of delivering closer to the existential-spatial human experience in the real world that will contribute to the development of building designs that match end-user's requirements effectively. These methods of design communication become even more challenging when the stakeholders involved lack technical skills, leading to a different cognition of the same design communicated, resulting in an entirely different representation of information (Zhang *et al*., 2021). Unlike other sectors of architecture, engineering and construction (AEC), FFE's design communication involves stakeholders with both technical and non-technical backgrounds making the communication process even more difficult (Chowdhury and Schnabel, 2020; Prabhakaran *et al*., 2021). Importantly, Kozhevnikov and Dhond (2012) suggested that design communication using 3D or 2D designs on 2D interfaces is ineffective or even counter-productive when compared with immersive 3D environments. Thus, for a design to be communicated effectively to all levels of stakeholders, communication media and representation of the design plays a vital role (Gopsill *et al*., 2013, 2015; Sinfield *et al*., 2020).

1.4. The need for a virtual and immersive approach to communication systems for the FFE sector

Like any other sector of the AEC industry, transparency of design information and data provides knowledgeability which is critical for the FFE sector's communication with project stakeholders in making well-informed decisions (Stoiciu, 2011). This knowledgeability and informed decisions can increase the quality of the design communication process by providing both relevance and validity to the outcome. As discussed earlier in section 1.3, traditionally in the FFE sector, various design communication methods, such as 2D drawings, sketches brochures or 3D renderings on 2D interfaces, were relied upon heavily to communicate designs with the stakeholders. However, these methods have proven to be lacking in communicating the complexity of spatial information with the stakeholders, especially when they are non-experts (Chowdhury and Schnabel, 2020). With the advancements in information and communication technology (ICT) and the advent of Industry 4.0, an increasing trend has been witnessed in the creation of a digital value chain that enables more effective communication between construction stakeholders (Bordegoni and Ferrise, 2013; Wen and Gheisari, 2020). Virtual reality, which is considered to be one of the major technological contributions to the digitalisation of the construction environment in Industry 4.0, has shown the potential to redefine radically the ways of communicating design information visually between various stakeholders in the FFE sector (Laing and Apperley, 2020; Wen and Gheisari, 2020). A wide range of definitions for VR exists in various literature (Rheingold, 1991; Brooks, 1999; Whyte *et al*., 2001; Burdea and Coiffet, 2003). However, the simplest definition for VR is "Pure Virtual Presence" where "the component of communication which takes place in a computer-generated synthetic space and embeds humans as an integral part of the system" (Regenbrecht and Donath, 1997). While various types of immersive virtual reality exist (detailed in Chapter 2), it is noted that, in this research, head-mounted, virtual reality technology is referred to as VR unless otherwise stated. Immersive technologies such as VR offer a revolution in the visual representation of objects and space through context awareness as well as the incorporation of information beyond

3D, offering countless opportunities for more effective design visualisation with the potential to assimilate the eclectic and fragmented process within the AEC industry, thereby enhancing communication and co-ordination between all stakeholders (Whyte, 2001; Greenwood *et al*., 2008; Prabhakaran *et al*., 2018). Various authors (e.g., Good and Tan, 1994; Oh *et al*., 2004, 2008; Yoon *et al*., 2010; Johnson *et al*., 2010; Kotler and Keller, 2012; Cotey, 2017) have shown that VR can offer significant opportunities for improved synergy between FFE design and wider construction that will facilitate the opportunity for all stakeholders to be immersed in a virtual environment that provides a unique, in-depth point of view to analyse the design through enhanced collaboration and communication. Berg and Vance, (2017) observed enhanced design communication between stakeholders through the implementation of VR during design reviews. This could aid the development of digital and virtual prototypes of FFE products that could be used to visualise and appraise designs by stakeholders as well as provide them with the opportunity to evaluate alternatives before they are produced, built, or incorporated into buildings (Cotey, 2017). VR could support the evaluation of the aesthetics of FFE products as well as other functional features that might be relevant to various stakeholders including users, clients and contractors when making decisions (Good and Tan, 1994; Whyte, 2001; Johnson *et al*., 2010; Kotler and Kevin, 2012; Cotey, 2017). Dossick and Neff (2011) and Du *et al*. (2018) noted that, unlike conventional design communication, with the help of shared 3D visualisation of information, VR can support asynchronous communication, which can reduce the communication and co-ordination latency, thus avoiding misinterpretation of information. Also, Chowdhury and Schnabel, (2020) indicated that the utilisation of VR for design communication facilitates a better understanding of the design for stakeholders with all levels of comprehension. This is attributed to the fact that, while perceiving representations in a virtual environment, the brain uses less working memory when compared with 2D design communication methods such as 2D paper and digital methods (Neubauer *et al*., 2010).

1.5. Knowledge gap

Evidence suggests that VR has great potential in the FFE sector as a design communication and collaboration tool. Existing VR applications, when integrated with FFE's workflow, assist stakeholders to experience the space before it is physically constructed and use VR as a spatial coordination tool (Good and Tan, 1994; Wang and Wang, 2008). The visual information that is conveyed through the virtual representation is beneficial for the FFE sector because the client's procurement decision is affected by information about colour, patterns, visual texture, ergonomics and material (Lee, 2009).

However, from an extensive review of the literature and state-of-the-art practice, it was identified that no studies have been undertaken to investigate the effectiveness of VR as a communication tool in FFE workflow. There is a strong perception in the FFE sector that the current utilisation of VR applications compromises their full potential as the environmental representation is focused predominantly on the visual modality regardless of other endless possibilities such as utilising attached meta-data to interact and manipulate the information-rich BIM model and improve the decision-making process through remote collaboration (Yoon *et al*., 2010; Prabhakaran *et al*., 2021). This poses an additional challenge as the knowledge and research of what constitutes an efficient and effective visualisation, collaboration and communication tool lag behind the rapidly evolving technology (Johnson *et al*., 2010; Wen and Gheisari, 2020). The stakeholders' decision-making process with respect to selection, space planning, or construction and assembly is influenced by factors such as need recognition, the quest for information, and alternative product evaluation (Lee, 2009; Kotler and Keller, 2012). It is noted that existing VR applications in the FFE sector are merely acting as a vehicle to maintain traditional visualisation practices, ignoring the above-mentioned critical factors together with human factors, behaviours and other perceptual and practical needs. Therefore, existing VR applications might be limited in ensuring full walk-throughs and construction sequence visualisation which are examples, however, of key user requirements in FFE design or construction communications (Greenwood *et al*., 2008; Johnson *et al*., 2010). Furthermore, like other sectors of construction, the stakeholder decision-making process in the FFE sector is hugely influenced by collaborative communication of designs (Lee, 2009; Truong *et al*., 2021). However, the current VR applications in the FFE sector are limited to a single-user virtual environment, thus lacking a collaborative virtual environment where a group of geographically remote stakeholders can interact, communicate effectively, and appraise designs collaboratively in real-time (Roupé *et al*., 2020). This is highly important for design communication in the FFE sector as perceptual awareness is a critical factor in the collaborative design communication process. Together with the impact of the COVID-19 pandemic, the need for a remote, collaborative environment that is intuitive and, at the same time, immersive is more prominent now than ever before (Syamimi *et al*., 2020; Truong *et al*., 2021). Cumulative evidence suggests that the current state of VR application in the FFE sector lacks three critical advancements, namely BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (multi-user interaction). In a bid to address these gaps, the aim of this research was to develop and test novel virtual environments for immersive communication between FFE and construction project stakeholders. Pre-conditions for the successful implementation of the developed immersive applications are evaluated further in the study through experimentation.

1.6. Research aim

The aim of this study was to develop and test novel virtual environment approaches and tools for FFE workflow. In particular, the study focused on examining the effectiveness of immersive communication between FFE and construction project stakeholders. Pre-conditions for the successful implementation of the developed immersive applications were evaluated further in the study through experimentation.

1.7. Research objectives

To achieve the aim of the study, the following stepwise objectives were addressed:

1) *Review state-of-the-art practice in the applications of virtual reality as an immersive method of communication in the AEC industry in general and FFE in particular in order to identify opportunities and application areas for VR and its use for improving communications and coordination of design in FFE.*
2) *Ascertain requirements for the development of useful FFE-specific VR applications for immersive communication.*
3) *Develop high-fidelity, interactive, and distributed VR applications based on the requirements identified.*

4) *Test the VR applications in various FFE construction project communication scenarios and workflows to ascertain utility, usefulness as well as challenges of implementation.*

5) *Validate the industry-wide usefulness of the developed VR applications and examine their effectiveness, focusing on challenges and benefits that affect/facilitate the stakeholder's intention to adopt VR applications for use in FFE.*

6) *Provide conclusions and recommendations for policy and practice as well as future research.*

1.8. Scope of research

The aim of this study was to develop and test novel virtual environments for immersive communication between FFE and construction project stakeholders. Pre-conditions for the successful implementation of the developed immersive applications were evaluated further in the study through experimentation. The study is of primary relevance to FFE stakeholders (architects, FFE designers, FFE contractors/suppliers, FFE manufacturers and end-users/clients) whose participation in design communication and collaboration is critical for the effective arrangement and utilisation of a facility's space. The term 'communication' in this research refers to the exchange of information both graphical and non-graphical between the FFE sector's stakeholders and their construction counterparts. The most predominant method of design communication and collaboration in the FFE sector was based mainly on traditional methods (2D paper, 2D digital and 3D models viewed on a 2D interface) and, to some extent, walk-throughs in various kinds of virtual environments. Thus, there was a need to develop immersive, virtual environments that would enable the FFE sector and construction project stakeholders to interact, communicate and collaborate effectively. The scenarios of communications in this study were limited to product selections for projects and their incorporation into a facility's interior design without any structural changes to the main architectural designs. The study was limited further to buildings in health care, education and commercial FFE scenarios predominantly in the UK.

1.9. Thesis format

The format adopted for the presentation of this thesis is the 'publication output' format as per the University of the West of England (UWE) Graduate School academic regulation (1.2 and 13.10). Based on these regulations, six of the thesis chapters presented (refer to Section 1.10, Figure 1.1 and Table 1.1) are research outputs (which have already been published or accepted for publication). The publication presented in this thesis as chapters systematically address the various objectives of the research (Figure 1.1). In addition, the remaining three Chapters (1, 8 and 9) provide a synthesis and overview of the combined contributions of the published outputs which form chapters of this thesis. According to the graduate school regulations (see 1.2.4), the research output presented in this thesis format does not have to have been published or accepted by publishers by the time of thesis submission, although in the case of this thesis, all outputs incorporated have been published or accepted for publication.

1.10.Organisation of chapters

This thesis is organised into nine chapters as shown in Figure 1.1. The contents of the chapters are summarised in the following sections. Further table 1.1 presents the timeline that contextualises the software development and/or experiment/ data collection that has contributed to each published chapter.

Chapter 1: In this chapter, the background of the research and the knowledge gap identified are presented together with the aim and objectives of the study. The methodological framework applied to this study is also presented in this chapter.

Chapter 2: This chapter is the first part of the literature review in phase one (Figure 1.1) that provides an overview of the FFE sector, its definition and scope within the AEC industry, methods of design communication and collaboration and the relevance and use of immersive technologies such as virtual reality. This chapter is presented in the form of an article which is accepted for publication in the proceedings of the Sustainable Ecological Engineering Design for Society (SEEDS) conference 2022.

Chapter 3: This chapter is the second part of the literature review in phase one (Figure 1.1) which is presented as a systematic review. Predicated on a wide range of scholarly literature, the application of immersive technology in the AEC industry as a whole is explored in this chapter and the challenges of utilising immersive technology in the construction industry are identified. This chapter is presented in the form of an article which was published in the Journal of Automation in Construction.

Chapter 4: This chapter contains a discussion of the development and testing (phase two) of the interactive VR application (Figure 1.1) for the FFE sector. Based on the testing, the effectiveness of VR as a design communication tool for the FFE sector is established in comparison with traditional methods of design communication. This chapter is presented in the form of an article which was published in the Journal of Engineering Construction and Architectural Management.

Chapter 5: This chapter contains a discussion of the development and testing (phase two) of the distributed VR application for FFE design communication and coordination in the construction sector context. This chapter is presented in the form of an article which was published in the Journal of Automation in Construction.

Chapter 6: This chapter contains a discussion of the usability of distributed VR in the FFE sector in a retail context. In this chapter, the results of the usefulness of the developed, distributed VR applications are recorded after the applications were tested specifically when applied in the retail segment of the FFE sector. This chapter was published as a book chapter in Springer, which is currently in press.

Chapter 7: In this chapter, the industry-wide usefulness of the developed VR applications are validated and their effectiveness is examined with a focus on the challenges and benefits that affect/facilitate the stakeholder's intention to adopt VR applications for use in FFE. This chapter is presented in the form of an article which was published in the Journal of Smart and Sustainable Built Environment.

Chapter 8: In this chapter, the key research findings are discussed with reference to the existing knowledge and literature. In the discussion, distinctions and parallels are drawn between the current study and previous related studies.

Chapter 9: The conclusions and recommendations based on this research are presented in this chapter together with contributions to knowledge, and the research limitations and implications of the findings are also detailed.

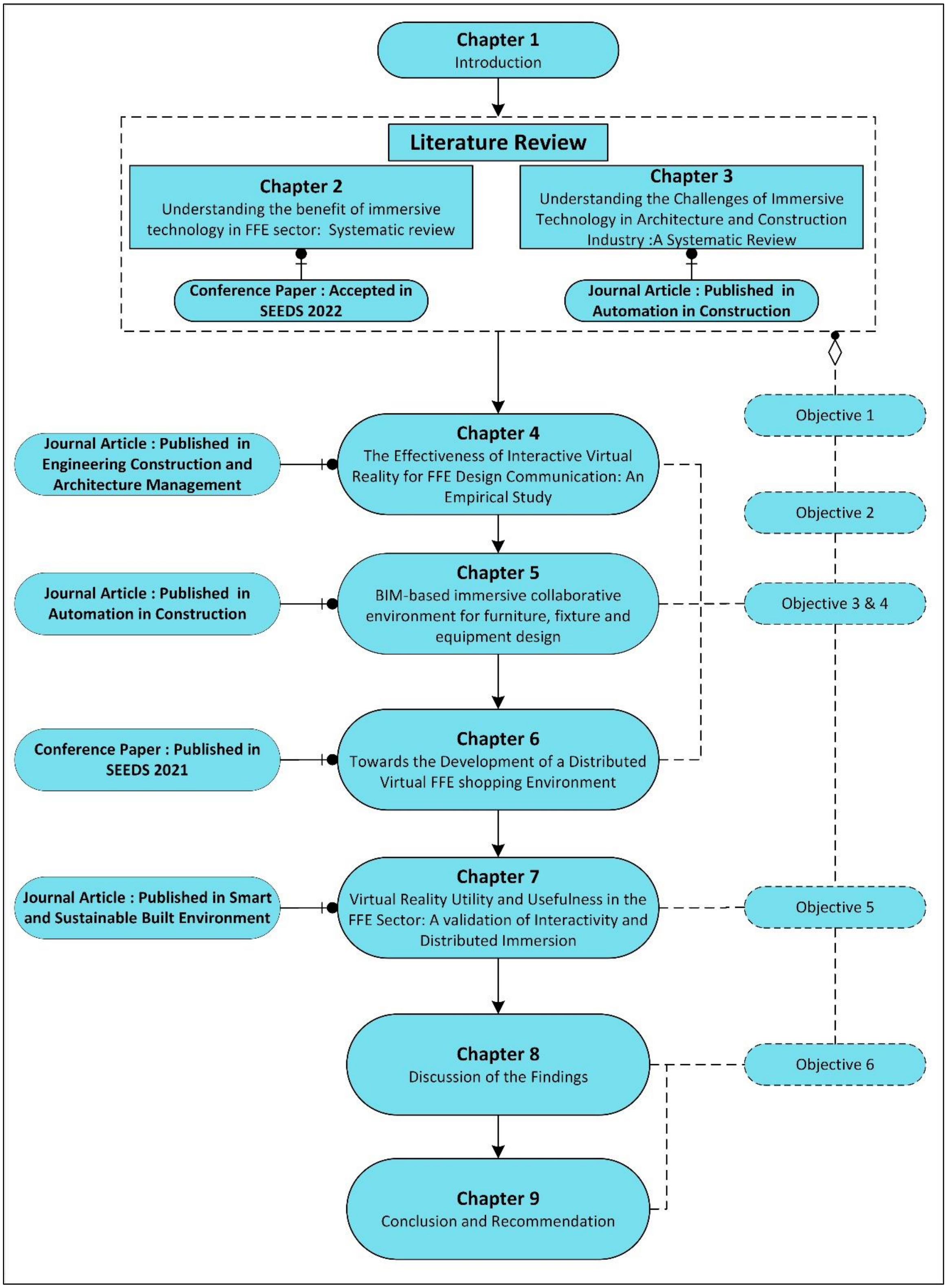

Figure 1.1: Organisation of chapters in the thesis

Table 1.1: Publication Timeline

Chapter	Application Development	Experiment/Data Collection	Initial Submission Journal/Conference	Accept on
2	N/A	May-July-2019	May 2022	June-2022
3	N/A	April-Nov-2019	Sept-2020	March-2022
4	Nov-Dec-2019	Jan-Feb-2020	April-2020	Nov-2020
5	June-Aug-2020	Oct-Dec-2020	July-2021	July-2022
6	Jan-2021	March- 2021	May 2021	July-2021
7	N/A	Aug-Nov- 2021	Feb-2022	April-2022

1.11. Scientific approach and methods

In order to break the barriers of limited literature and data sources because of the novelty of VR in the context of use in the FFE sector, a methodological pluralism that encourages the use of multiple methodological approaches was proposed as an appropriate research method for this study (Creswell *et al*., 2003; Knight and Ruddock, 2009). A pragmatic research philosophy was adopted for this study because this research philosophy embodies the flexibility of integrated use of multiple research approaches and strategies, as noted by Dudovskiy (2018). Greene (2007) also argued that pragmatism is the most popular paradigm for mixed-method research. By adopting a pragmatic philosophical stance, the research problem and research questions are placed at the centre of the research and the methods considered to be the most suitable for deriving the most significant insight into the research are applied (Wilson, 2014). However, the selection of the strategy was based solely on the objectives, data availability and analysis proposed. As this study includes multiple objectives that are beyond a single worldview or research design, Mahamadu (2016) noted that research methodologies could be adopted accordingly that are adequate to address the research objectives. Furthermore, because construction and information science represent a multi-disciplinary domain of inter-connecting areas of specialisation, it was necessary

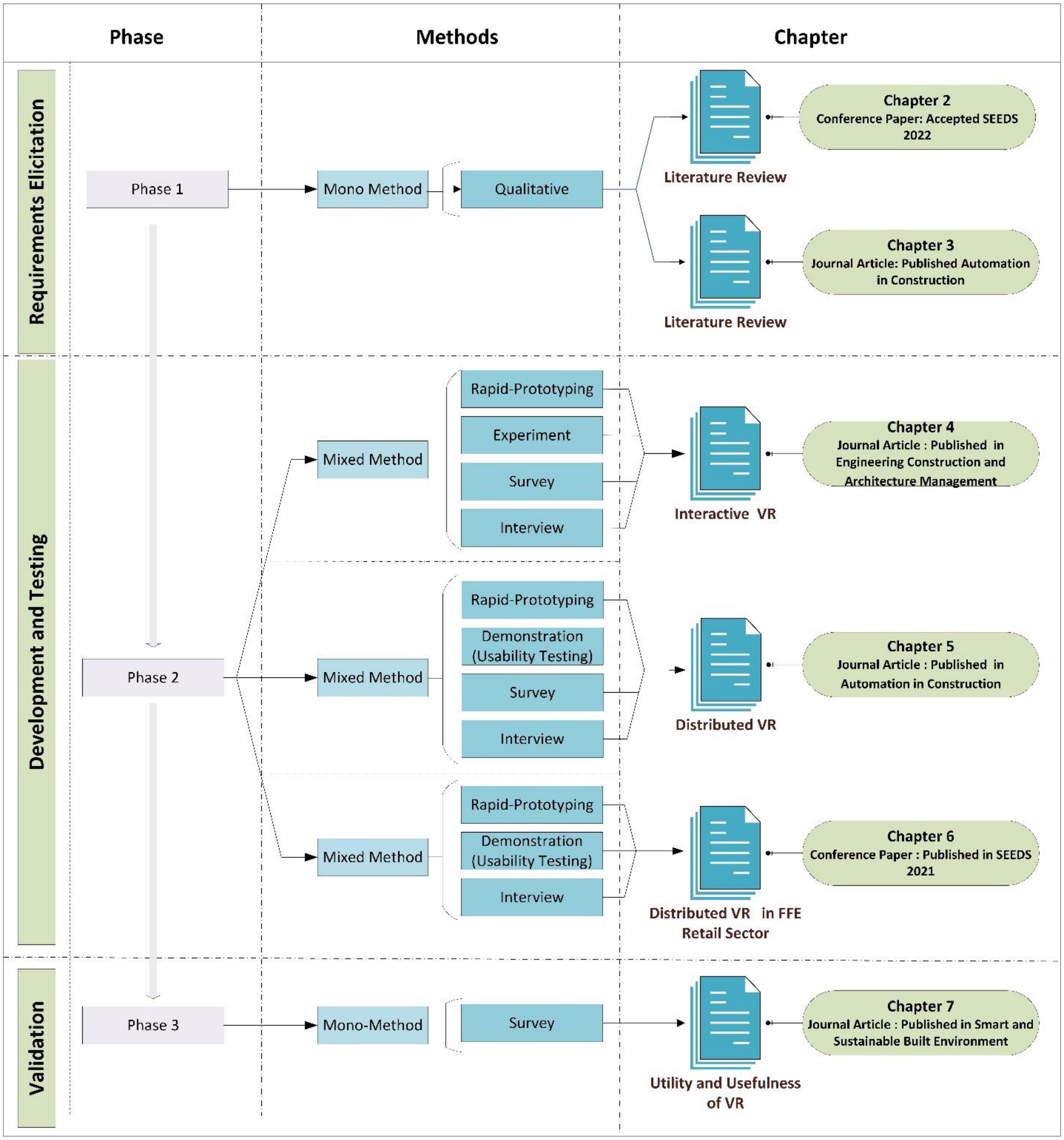

Figure 1.2: Research methodology framework

to adopt a balanced approach, as observed by Mahamadu (2016)). Even though mixed-method analysis is labour-intensive and requires more resources and time when compared with a single-method study, the results are more reliable (Wisdom and Creswell, 2013). In line with the pragmatic stance, multiple methods were chosen in three distinct research phases as detailed in the research framework (Figure 1.2).

Table 1.2: List of Published Chapters

Chapter	Type	Publication	Status	Note
Chapter 2	Conference Paper	Sustainable Ecological Engineering Design for Society	Accepted	Chair's Award
Chapter 3	Journal Article	Automation in Construction	Published	10.51 (IF*)
Chapter 4	Journal Article	Engineering, Construction and Architectural Management	Published	4.12 (IF*)
Chapter 5	Journal Article	Automation in Construction	Published	10.51 (IF*)
Chapter 6	Book Chapter	Springer	In press	Practical and Smart Innovation Award
Chapter 7	Journal Article	Smart and Sustainable Built Environment	Published	5.0 (CS**)

***IF Impact Factor, **CS CiteScore**

In phase one of the study, an in-depth literature review was carried out. Saunders *et al*. (2015) describe literature research and review as an upward spiral where the process starts from the early stage of the research project extending throughout the project's life. An extensive literature investigation was carried out to acquire a deeper knowledge of existing literature to understand the up-to-date developments of immersive technologies. The literature review was focused specifically on the implications of the latest developments in immersive technology in promoting effective communication, coordination and decision-making in the construction sector with special attention to the FFE sector and BIM, as well as the current challenges of mainstreaming immersive technology in the construction industry. The identification of these challenges aided in implementing mitigation plans during the development phases and understanding the usefulness and utility of the developed VR application during phase three (validation).

In the second phase of the research, two VR applications (interactive and distributed VR) were developed and tested for their usefulness and utility in the FFE sector. A rapid application development (RAD) model (Martin, 1991) was adopted for the development phase of this study. RAD prioritises rapid prototype release and iteration in the software development process (Beynon-Davies *et al*., 1999). Although RAD and agile methodologies, such as SCRUM, share similar values in terms of flexibility, shorter delivery time, as well as higher stakeholder interaction and satisfaction, RAD, in particular, emphasises rapid prototyping and was specifically chosen over other agile methods because of relative advantages in terms of cost, time, work focus and process flexibility (Beynon-Davies *et al*., 1999; Aryanto *et al*., 2021). Beynon-Davies *et al*. (1999) suggested that RAD is the most appropriate application development method when the application is highly interactive, and the stakeholder group is clearly defined. Both of the VR applications developed for this study were highly interactive and the targeted users were FFE stakeholders. The developed VR applications were tested for their effectiveness and usefulness among the FFE stakeholders, using surveys and interviews. Furthermore, in the third phase of the study, the developed VR applications were validated for their industry-wide usefulness and examined for their effectiveness with a focus on challenges and benefits that affect/facilitate the stakeholder's intention to adopt VR applications for use in the FFE sector.

1.12. Chapter summary

In this chapter, the background of this research and the inefficiencies of the current design communication and coordination methods in the FFE sector were discussed. A need for an interactive and distributed virtual environment for design communication and coordination was identified. The research aims and objectives were presented together with the methodological framework adopted for this research. In the next chapter, an in-depth literature review was carried out to understand the state-of-the-art immersive technology applications and the benefits offered by them to the FFE sector.

Chapter 2: Understanding the Benefits of Immersive Technology Use in the Furniture Fixture and Equipment Sector: A Systematic Review

Abhinesh Prabhakaran[1], Abdul-Majeed Mahamadu[23], Lamine Mahdjoubi[1] and Colin A. Booth[1]

[1]Department of Architecture and the Built Environment, University of the West of England, Bristol, BS16 1QY, United Kingdom.

[2] The Bartlett school of Sustainable Construction, University College London

[3]Department of Construction Management and Quantity Surveying, University of Johannesburg, Johannesburg.

Prabhakaran, A., Mahamadu, A., Mahdjoubi, L., and Booth, C. A. (2022-*Accepted*). Understanding the Benefits of Immersive Technology Use in the Furniture Fixture and Equipment Sector: A Systematic Review: *Sustainable Ecological Engineering Design for Society (SEEDS)*.

Statement of Contribution: This conference paper is a systematic review carried out to gain a better understanding of state-of-the-art immersive technology applications in the FFE sector with a focus on the benefits of immersive virtual reality for the FFE sector. My contribution as the main author of this article included conceptualisation, development and implementation of the research, identification and synthesis of the literature, analysis and discussion of the results, draft and revise the paper based on the reviewers' comments. Co-authors of this paper are my PhD research supervisors who provided the mentorship, guidance, review of research concepts, methods and review of manuscripts. My overall contribution to this paper is estimated between 80-90%.

Abstract

Like other sectors of the Architecture, Engineering and Construction (AEC) industry, immersive technology has proven to be an effective tool in the Furniture Fixture and Equipment Sector (FFE), which recently attracted a lot of attention from researchers. Despite the increasing scholarly attention being given to immersive technology applications in the FFE sector, very few studies have explored the key benefits associated with the application of immersive technology in this sector, with no aggregation of findings and knowledge. To bridge this gap and to gain a better understanding of the state-of-the-art immersive technology application in the FFE sector, this study reviews and synthesis the existing research evidence through a systematic review. The relevance of this study cannot be overemphasised, given the vast number of published works albeit a lack of aggregation of the findings and knowledge. After a thorough search of key academic databases, a full range of journal articles and conference papers published between 2010 and 2022 (inclusive) that address the application of immersive technology in the FFE sector was systematically assessed. Built upon rigorous inclusion and exclusion criteria, 24 eligible literature was identified and reviewed. Predicted on a wide range of scholarly literature, this study identifies 20 critical benefits associated with the application of immersive technology in the FFE sector. This study provides an opportunity for the FFE sector to understand the benefits associated with the adoption of immersive technology that will encourage the adoption of immersive technology in the FFE sector which is in the process of digitisation.

Keywords: Design Communication, Productivity and Efficiency, User Experience, Immersive Collaboration

2.1. Introduction

Design communication and coordination in the Furniture Fixture and Equipment (FFE) sector were mainly based on traditional methods (2D drawings, sketches, broachers and 2D digital), which have proven to be cumbersome and inefficient (Mahdjoubi *et al*., 2014). This was often attributed to the fact that FFE's design communication and coordination are heavily reliant on visual information and the traditional methods are incapable to provide a full understanding of the architectural aspect of a building (Mahdjoubi *et al*., 2014). Through the adoption of BIM, the FFE sector has been able to convey its design to stakeholders more effectively. However, as building designs have become complex, visualising such complex 3D models on 2D interfaces (e.g., a computer screen/monitor) has proven to be challenging (Chalhoub and Ayer, 2018), particularly when the stakeholders lack technical skills (Prabhakaran *et al*., 2021; Mahamadu *et al*., 2022). In a bid to address this, immersive technology (ImT) has been widely recognized by the FFE sector for its ability to deliver a multi-sensory three-dimensional environment that can immerse stakeholders in a virtual environment specifically for fulfilling high demand, visual forms of design communication and coordination during the planning of a space (Prabhakaran *et al*., 2021).

Several studies have identified various benefits associated with the application of ImT in the FFE sector. However, there has been no research in which these benefits have been integrated systematically and collectively. Therefore, this study aims to fill this gap by consolidating the benefits of ImT targeting the FFE sector by conducting a systematic review. A systematic review in this area will be highly beneficial for a sector like FFE that is on the path of digitisation and this study will assist in research, decision-making and policies by integrating critical information. After a thorough search of key academic databases, a full range of journal articles and conference papers published between 2010 and 2022 (inclusive), which address the application of ImT in the FFE sector, will be systematically assessed in the following sections.

2.2. Literature Review

2.2.1. Design Communication in FFE Sector

Even though the definition of FFE is surrounded by some ambiguities, NBS (2010) defines FFE based on the Common Arrangement of Work Section (CWAS) with a better consistency of the terminology, stating that "FF and E are classed as movable furniture, fixtures or other equipment that have no permanent connection to the structure of a building or utilities". For this study, the NBS definition of FFE is adopted in view of its encapsulation and better consistency of the terminologies. In the UK, the FFE sector forms part of both the construction supply chain and the retail industry; thus, belonging to a wider spectrum of the market (Zenner *et al*., 2020). Moreover, the construction stakeholders also form part of the FFE's retail segment depending on the size of the project. The FFE sector is a critical segment of the construction industry and remains the single greatest determinant of a building's day-to-day functionality, which could conceivably influence the architectural aspects of a facility (Yu *et al*., 2021). FFE occupies a significant role in any facility, and can constitute approximately 12–16% of a construction budget and sometimes even 40% (the health care industry has the highest budget for FFE products) of the overall construction budget (Fryer, 2012). Similarly, the relevance of the retail segment of FFE cannot be overemphasised considering the contribution it makes to the UK's GDP (£12.5 billion), and the number of employments it creates in the UK (339,000 persons) (The British Furniture Confederation, 2018). Thus, both segments of the FFE sector are value drivers that must not be underestimated (Fryer, 2012).

The methods used for communicating the designs with the stakeholders (e.g. 2D plans, sketches, brochures), in both segments of FFE, are more or less the same; hence, the term "FFE sector" in this review is used to represent both construction and retail segments. FFE sectors' communication of design follows a linear flow of information among the stakeholders, starting from the designer (in the case of the retail segment this will be the sales team) to the end-user/client. This mode of communication is often referred to as the linear standard communication process, where the messages at the transmitting end are encoded and receiving end decodes the message (Shannon, 1948). This process of encoding and decoding the message results in noises in the communication transmitted (Shannon, 1948). FFE sector's communication of design is mainly based on 2D (paper-based and digital), resulting in poor stakeholder engagement and a decline in productivity because of the noise created during the decoding stage. Further, both segments of FFE comprise stakeholders with technical and non-technical capabilities (in the retail segment, non-technical traits are more frequent), which makes the design communication process more complex (Mahdjoubi, 2014; Prabhakaran *et al*., 2021). Further, the design communication and resulting decision-making process in the FFE sector involves consideration of constraints, such as cost, space, availability and aesthetic aspects (Oh *et al*., 2010), which can lead to uncertainty among stakeholders over whether they have made the correct design choice. One of the important reasons for such uncertainty is the resultant of the stakeholder's inability to comprehend the design in the context of the facility for which the FFE elements are designed (Hall and Tewdwr-Jones, 2010). In this context, visual representation and spatial perception offered by ImT play a critical role in communicating the design effectively. In the next section, the role of ImT in enhancing design communication and collaborative decision-making is detailed.

2.2.2. Immersive Technology for Design Communication and Co-ordination

Lee *et al*. (2013) define ImT as a technology that is capable of delivering users a sense of immersion through blurring the boundary between real and virtual environments (VE). The ImT has evolved rapidly in recent years owing to its flexibility in being adapted to various problems and domains (Zenner *et al*., 2020). Over the years a variety of VE with various levels of immersion and capability has evolved (Spaeth and Khali, 2018). These levels can be passive VE, which is referred to as spectator activity, such as watching TV, exploratory VE involves interacting with a 3D environment but on a 2D interface and immersive VE where users can interact and immerse fully with an artificial environment (Spaeth and Khali, 2018). Therefore, this study only examines the latter category of ImT and its application in the FFE sector for immersive design communication and coordination.

The flexibility to adapt and the capability to immerse users in a virtual environment has shown great potential in the application of ImT for design communication during the space planning of a facility (Prabhakaran *et al*., 2021). When a 3D design is viewed on a 2D interface (exploratory VE), the users are unable to gain the spatial notion of depth, which is otherwise accrued while visualising in an immersive VE (Spaeth and Khali, 2018). Gurevich and Sacks (2014) suggest that the application of ImT during space plaining allows stakeholders to assess the functionality of space on a true scale, by creating a direct relation to the body. This capability of ImT to provide spatial perception has a profound effect on improving design communication and collaboration, which has captured the attention of industry and academics alike. Despite the scholarly attention being given to ImT applications in the FFE sector, very few studies have explored the key benefits associated with the application of ImT in the FFE sector, with no aggregation of findings and knowledge. To bridge this gap and to gain a better understanding of the state-of-the-art ImT application in the FFE sector, this study reviews and synthesis the existing research evidence through a systematic review and present a synthesis of the evidence available thus far on the benefits associated with the application of ImT within the FFE sector.

2.3. Research Methodology

To comprehensively explore the benefits that ImT can offer to the FFE sector, a systematic review supported by qualitative analysis was conducted. The qualitative analysis was best suited for this study as it aids in identifying empirical evidence from various studies that help in achieving greater understanding and accruing a higher level of conceptual and theoretical knowledge of the benefits ImT can offer during the FFE sector (Chamber, 2004). The study consists of four stages: (a) identification of literature; (b) review of literature; (c) definition of a classification framework; and (d) classification of literature based on the framework.

To identify relevant literature within the scope of this study, inclusion and exclusion criteria were developed. The inclusion and exclusion criteria were developed based on two key questions proposed by (Meline, 2006), namely: (a) is the study relevant for the review purpose? and (b) is the study acceptable for review? These lay the foundation for the development of reliable inclusion and exclusion criteria. Chamber (2004) noted that reliable inclusion and exclusion criteria will reject a large proportion of the articles. This might be considered a limitation of this study, however, applying reliable inclusion and exclusion criteria ensures the quality of the review process.

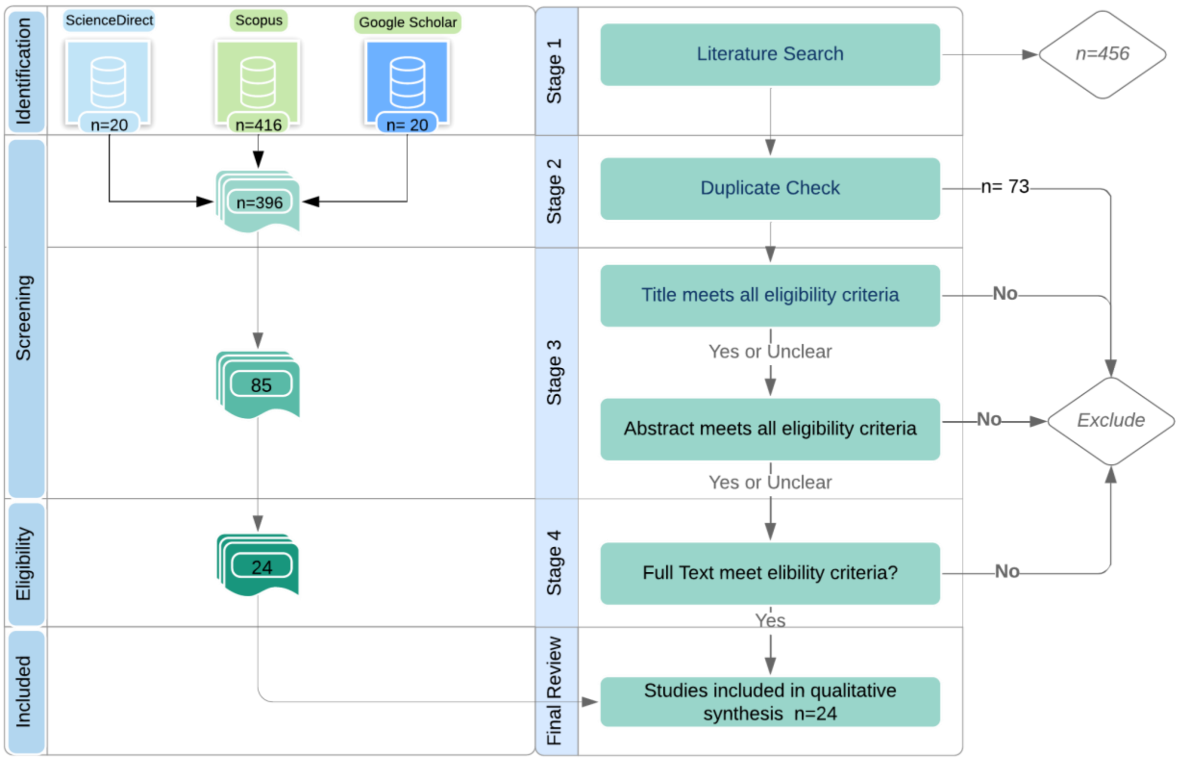

Figure 2.1: Literature identification process based on the PRISMA framework

2.3.1. Inclusion-Exclusion Criteria

- Articles published between 2010 and 2022 (inclusive) were only considered to maintain concurrency.
- Articles that utilise ImT (as per the definition in Section 3) were only considered.
- Only peer-reviewed journal and conference papers were considered to maintain a predetermined threshold of quality.
- Articles that discuss theory concepts or proposals without any empirical testing were excluded.

The systematic review process (Figure 2.1) was based on the preferred reporting items for the systematic literature review and meta-analysis (PRISMA) framework (Moher, *et al*. 2009). A total of three databases (Google Scholar, Scopus, and Science Direct) were searched for relevant articles using the keywords (“Furniture” OR “Fixture” OR “FFE” OR “Interior”) AND (“Virtual Reality” OR “Mixed Reality” OR “Immersive Technology”).

2.4. Results and Discussion

A total of 24 eligible published articles were identified for this study based on the PRISMA framework. Scrutiny of those works enabled the identification of 20 critical benefits (Table 2.1) that can be achieved through the utilisation of ImT in the FFE sector.

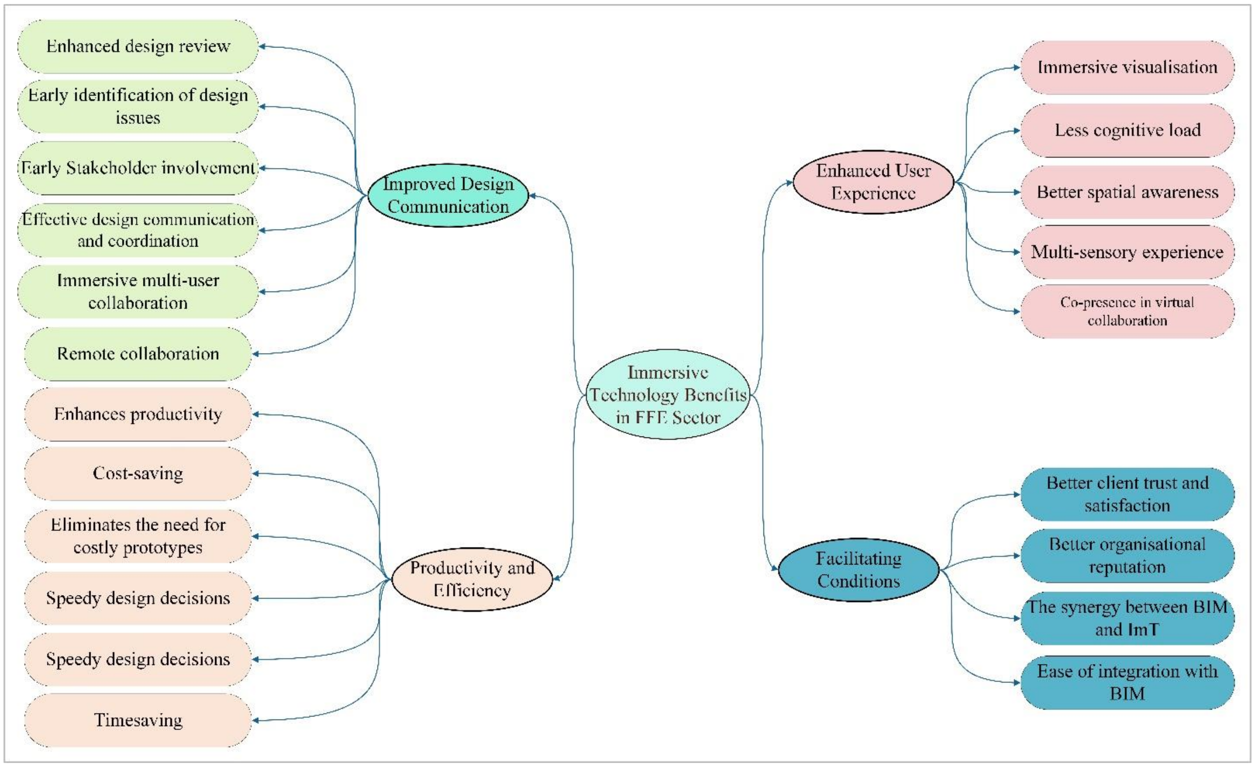

Figure 2. 2: Benefits offered by Immersive Technology to the FFE Sector

These benefits were further classified based on the ground theory method, which is one of the popular methodologies for categorising literature in ICT (Urquhart *et al*., 2009). Based on the grounded theory methodology, four classification frameworks were derived: (a) Improved design communication; (b) enhanced user experience; (c) facilitating conditions; (d) productivity and efficiency. Figure 2.2 presents the classification framework and the benefits associated with them.

Figure 2.3 presents the number of articles based on the classification framework. The benefits and the classification factors were ranked based on the number of articles reported (Table 2.1). Productivity and efficiency were reported as the topmost beneficial factors for the FFE sector through the implementation of ImT, followed by enhanced user experience, improved design communication and facilitating conditions.

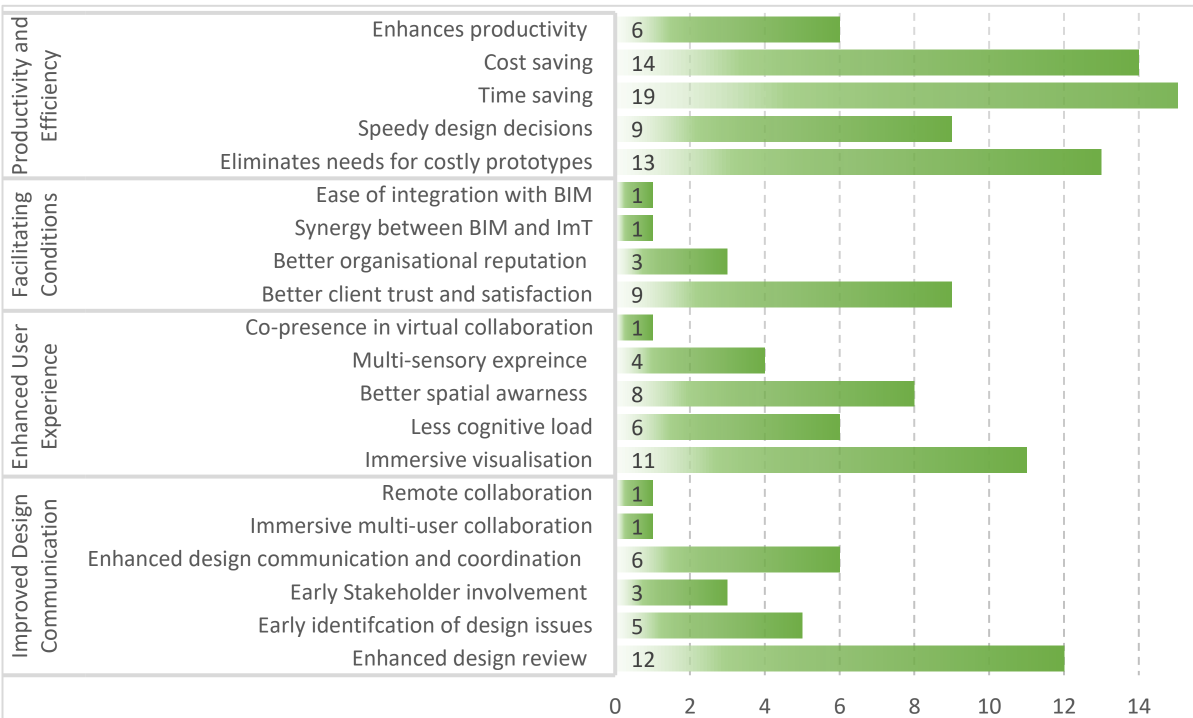

Figure 2.3: Quantities of articles based on the classification framework

2.4.1. Productivity and Efficiency

The FFE sector on its own is estimated to contribute about £11 billion to the UK's GDP and employs more than 339,000 workers (The British Furniture Confederation, 2018). However, for various reasons, like all other sectors of the construction industry, the FFE supply chain continues to face challenges that impede its competitiveness, as well as its performance (AMA Research, 2014). A report by Barbosa *et al*. (2017) highlighted productivity and performance decline

Table 2.1: Ranking of benefits and classification factors

Factors	Rank	Benefits	Rank	Reference
Improved Design Communication	3	Enhanced design review	4	Chalhoub and Ayer, 2018 ; Mahamadu *et al*., 2022; Prabhakaran *et al*., 2021
		Early identification of design issues	9	Du *et al*., 2018 ; Yoon *et al*., 2010 ; Oh *et al*., 2004
		Early Stakeholder involvement	11	Chalhoub and Ayer, 2018 ; Mahamadu *et al*., 2022
		Effective design communication and coordination	8	Yoon *et al*., 2010; Prabhakaran *et al*., 2021
		Immersive multi-user collaboration	13	Saeidi *et al*., 2019; Truong *et al*., 2021
		Remote collaboration	14	Saeidi *et al*., 2019; Truong *et al*., 2021; Prabhakaran *et al*., 2022
Enhanced User Experience	2	Immersive visualisation	5	Mahamadu *et al*., 2022 ; Oh *et al*., 2004 ; Truong *et al*., 2021
		Less cognitive load	8	Prabhakaran *et al*., 2021 ; Mahamadu *et al*., 2022
		Better spatial awareness	7	Yu *et al*., 2021 ; Zenner *et al*., 2020
		Multi-sensory experience	10	Zenner *et al*., 2020
		Co-presence in virtual collaboration	15	Saeidi *et al*., 2019; Truong *et al*., 2021; Prabhakaran *et al*., 2021
Facilitating Conditions	4	Better client trust and satisfaction	6	Zenner *et al*., 2020 ; Prabhakaran *et al*., 2021
		Better organisational reputation	12	Saeidi *et al*., 2019; Zenner *et al*., 2020
		The synergy between BIM and ImT	16	Prabhakaran *et al*., 2021 ; Mahamadu *et al*., 2022
		Ease of integration with BIM	17	Prabhakaran *et al*., 2021 ; Mahamadu *et al*., 2022
Productivity and Efficiency	1	Eliminates the need for costly prototypes	3	Yu *et al*., 2021 ; Zenner *et al*., 2020 ; Yoon *et al*., 2010
		Speedy design decisions	6	Yu *et al*., 2021 ; Zenner *et al*., 2020 ; Mahamadu *et al*., 2022
		Timesaving	1	Prabhakaran *et al*., 2021; Yoon *et al*., 2010
		Cost-saving	2	Prabhakaran *et al*., 2021; Yoon *et al*., 2010
		Enhances productivity	8	Saeidi *et al*., 2019 ; Yu *et al*., 2021 ; Truong *et al*., 2021

in the FFE sector are attributed to the lack of innovation and adoption of digital processes, such as Building Information Modelling (BIM) and ImT (Garcia, 2017). Through BIM, data visualisation can be supported by ImT for virtual representation of the FFE products within virtual or real spaces beyond 3D (Whyte, 2001; Greenwood *et al*., 2008; Prabhakaran *et al*., 2020). This could aid the development of digital and virtual prototypes of FFE products, which could be used to visualise and appraise designs by stakeholders, as well as allow them the opportunity to evaluate alternatives before they are produced, built or incorporated into buildings (Cotey, 2017). Thus, ImT cannot only improve the design communication but also reduce cost and time, and identify issues in advance. For this review, it was identified that cost and time saving are the two topmost benefits ImT available to the FFE sector. Thus, for a sector that often operates on low-profit margins (Prabhakaran *et al*., 2021 and 2022), these cost and time savings can make a huge impact on the sustainability of the sector. Furthermore, it is predicted that ImT's application in the whole construction industry could boost productivity, adding an estimated USD 1.6 trillion (Yu *et al*., 2021). Bening a critical segment in the construction industry, these added values will have a definite impact on the FFE sector.

2.4.2. Enhanced User Experience

The significance of FFE in connecting occupants and the built environment cannot be overemphasised considering the fact that humans spend 90% of their time indoors (Ergan *et al*., 2019). This puts a huge responsibility on designers/architects to design the space with utmost care so that the result satisfies the end-users needs both aesthetically and functionally. However, the design communication and decision-making process in the FFE sector is typically complex, involving consideration of various constraints such as cost, space availability, quality and aesthetics (Oh *et al*., 2010). The result of such a complex and vital decision-making process is the uncertainty among stakeholders over whether they have made the right choice. One of the reasons for such uncertainty is stakeholder inability to experience the space before they have been designed (Hall and Tewdwr-Jones, 2010).

Studies suggest that the ImT's application in the FFE sector can deliver a compelling and meaning full experience to the users before the space has been built. It also provides spatial awareness and multi-sensory experience to the stakeholders, which are impossible to achieve when viewed on a 2D medium (Prahakarran *et al*., 2021). However, a strong concern exists in the FFE sector that the current utilisation of ImT applications compromises its full potential as the environmental representation purely focuses predominantly on the visual modality regardless of other endless possibilities of BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) (Yoon *et al*., 2009; Prabhakaran *et al*. 2022). Further, the review has identified that existing ImT applications in the FFE may be limited in ensuring full walkthroughs and construction sequence visualisation, which are examples of key user requirements in FFE design or construction communications (Greenwood *et al*., 2008; Johnson *et al*., 2010). This poses an additional challenge as the knowledge and research of what constitutes an efficient and effective visualisation, collaboration and communication tool lags behind rapidly evolving technology (Johnson *et al*., 2010). Stakeholders' decision-making, with respect to selection, space planning, or construction and assembly, is influenced by factors such as need recognition, the quest for information, and alternative product evaluation (Lee, 2009). Thus, existing ImT applications are merely acting as a vehicle to maintain traditional visualisation practices, ignoring the above-mentioned critical factors along with human factors, behaviours and other perceptual and practical needs (Johnson *et al*., 2010).

2.4.3. Improved Design Communication

This review has identified improved design communication as the third most reported benefit offered by ImT for the FFE sector. The FFE sector exists in a dynamic environment involving various stakeholders (FFE designers, architects, contractors and client/end-users) to communicate its design constantly with each other. Prabhakaran *et al*. (2022) noted that stakeholders of the FFE sector consist of technical and non-technical capabilities, which determine their design comprehension capabilities. However, efficient design comprehension is necessary for effective design communication, which is critical for space planning. As mentioned earlier, FFE's design communication relies heavily on traditional methods (2d paper and digital) to facilitate design communication, which has proven to be inefficient (Mahdjoubi *et al*., 2014). However, the utilisation of ImT for design communication has proven to be a step-change in current methods of design communication in the FFE sector, through environments that can support synchronous communication with shared 3D visualisation of information to eliminate communication latencies and misinterpretations of designs caused by traditional methods of design communication. Further, current ImT applications allow concurrent multi-users to interact, communicate and collaborate virtually during design decision-making in the FFE sector. However, a dearth in literature, which utilises the multiuser functionality, that will allow human-human interaction in a virtual environment has been identified in this study. This could be attributed to the fact that the development process for such multi-user ImT applications is complex and the infrastructure requirements for such developments are resource-demanding (Podkosova *et al*., 2016). It is suggested that developments in ImT application in the FFE sector should focus on this shortcoming.

2.4.4. Facilitating Conditions

This study identified facilitating conditions as the fourth reported benefit ImT can offer to the FFE sector. Various studies report that the development of the virtual environment is one of the greatest challenges that restrain the adoption of ImT applications in the FFE sector. Rapid developments in ICT, especially ImT (i.e. virtual, augmented and mixed reality (VR/AR/MR applications), have offered new opportunities to address the communication and engagement gap in the FFE sector, which has offered a reliable extension of BIM for more advanced visualisation, as well as communication (Bordegoni and Ferrise, 2013). Through BIM, data visualisation can be supported by ImT for virtual representation of the FFE products within virtual or real spaces beyond 3D (Whyte, 2001; Greenwood *et al*., 2008). This could aid the development of digital and virtual prototypes of FFE products, which could be used to visualise and appraise designs by stakeholders, as well as allow them the opportunity to evaluate alternatives before they are produced, built or incorporated into buildings (Cotey, 2017). ImT can potentially support the evaluation of the aesthetics of FFE products, as well as other functional features that may be relevant to various stakeholders including users, clients and contractors when making decisions (Whyte, 2001; Johnson *et al*., 2010; Cotey, 2017).

2.5. Conclusion and Recommendations

This study aimed to identify the benefits of ImT application within the FFE sector. A full range of articles published between 2010- and 2022 (inclusive) that utilise ImT applications in the FFE sector was systematically assessed. Based on the PRISMA and rigorous inclusion and exclusion criteria, 24 eligible articles were identified for final review. A total of 20 critical benefits were identified from this review, which was categorised based on a generic taxonomy that was developed using grounded theory. The review revealed that productivity and efficiency as the topmost beneficial factor ImT can offer to the FFE sector followed by Enhanced user experience, Improved Design Communication and Facilitating Conditions. This study also identified a paucity of studies that utilises critical advancements in the application of ImT in the FFE sector namely BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (multi-user interaction). The findings from this study will be highly beneficial for sectors such as FFE which is on the path of digitisation. However, it is worth noting that most of the articles identified in this study have tested prototype applications. Hence these applications need to be assessed by both academia and industry for their features and value for money. Furthermore, the industry should also consider the challenges associated with the adoption of immersive technology applications so that mitigation plans could be devised in order to reap the benefits identified in this study.

Chapter 3: Understanding the Challenges of Immersive Technology Use in the Architecture and Construction Industry: A Systematic Review

Abhinesh Prabhakaran[1], Abdul-Majeed Mahamadu[1], Lamine Mahdjoubi[1]

[1]Department of Architecture and the Built Environment, University of the West of England, Bristol, Frenchay Campus, BS16 1QY, United Kingdom.

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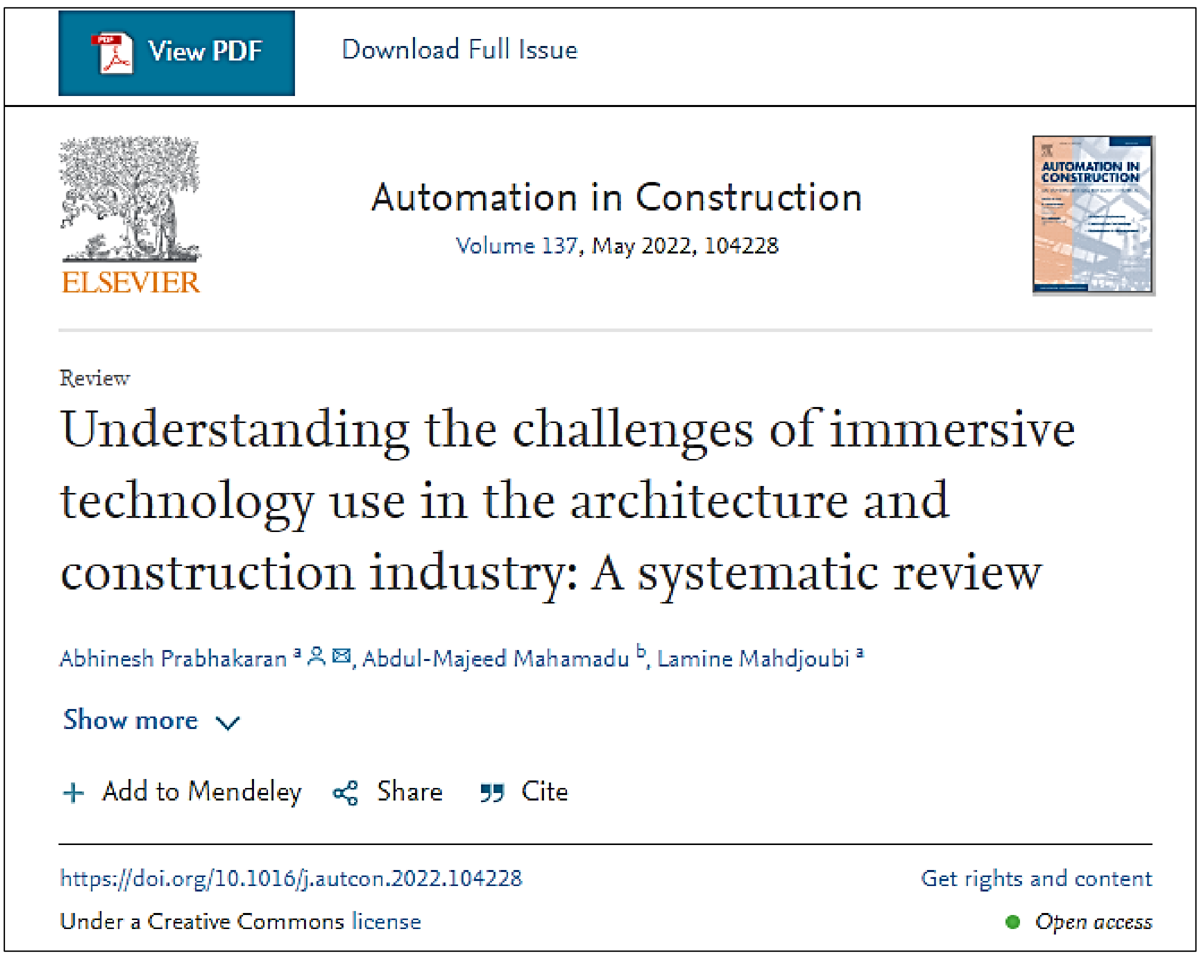

Statement of Contribution: This journal article was a systematic review carried out to gain a better understanding of state-of-the-art immersive technology applications in the architecture and construction industry with a focus on the challenges of immersive virtual reality. My contribution as the main author of this article included conceptualisation, development and implementation of the research, identification and synthesis of the literature, analysis and discussion of the results, draft and revising the paper based on supervisors' and reviewers' comments. Co-authors of this paper are my PhD research supervisors who provided the mentorship, guidance, review of research concepts, methods and review of manuscripts. My overall contribution to this paper is estimated between 80-90%.

Abstract

Despite the increasing scholarly attention being given to immersive technology applications in the architecture and construction industry, very few studies have explored the key challenges associated with their usage, with no aggregation of findings or knowledge. To bridge this gap and gain a better understanding of the state-of-the-art immersive technology application in the architecture and construction sector, this study reviews and synthesises the existing research evidence through a systematic review. Based on rigorous inclusion and exclusion criteria, 51 eligible articles published between 2010 and 2019 (inclusive) were selected for the final review. Predicted upon a wide range of scholarly journals, this study develops a generic taxonomy consisting of various dimensions. The results revealed nine (9) critical challenges which were further ranked in the following order: Infrastructure; Algorithm Development; Interoperability; General Health and Safety; Virtual Content Modelling; Cost; Skills Availability; Multi-Sensory Limitations; and Ethical Issues.

Keywords: Immersive technology, Systematic review, Challenges, Virtual reality, Mixed reality, CAVE

3.1. Introduction

Like many other aspects of our life, the Architecture and Construction (A and C) industry is also affected by the implications of the revolution caused by recent advancements in Information and Communication Technology (ICT). Modernisation was one of the biggest challenges faced by the A and C industries. Recently, however, the A and C industry has been exposed constantly to new, innovative tools and technologies, which are capable of improving stagnant productivity. Immersive Technology (ImT) is one such advancement, embraced by the A and C industry. ImT can be described as the use of technology to emulate the physical world in the form of a digital or simulated world in which a sense of immersion is created (Cummings and Bailenson, 2016).

Communication with stakeholders in the A and C industry has always been heavily reliant on visual means such as sketches, two dimensional (2D) drawings and images (Kim *et al*., 2013). Further advancements in technology, such as Building Information Modelling (BIM), made it possible to project designs in three dimensions (3D), which profoundly revolutionised this sector (Azhar *et al*., 2012). However, the visualisation of such complex 3D information on a 2D interface was still very inefficient and reduced the productivity of this industry (Laval Virtual, 2018). Since it became evident that the complexity of 3D building designs exceeded the ability of construction stakeholders to comprehend (Walasek and Barszez, 2017), the industry embraced ImT as an effective tool that could be applied in multi-dimensional aspects of construction activity such as visualisation, coordination, communication and training (Portman *et al*., 2015). Many studies that are focused on the use of ImT in the A and C industry are now available (Heydarian *et al*., 2015; Heydarian *et al*., 2017; Osello *et al*., 2018; Wang *et al*., 2018). It has been identified in these studies that many of the critical problems that arise in the A and C sectors are directly related to the inability of site personnel, designers, architects and engineers to experience a project truly before it is executed. In this context, the exciting opportunity for visualisation and interaction offered by ImT captured the attention of the A and C industry (Kim *et al*., 2013).

A series of efforts were undertaken during the 1980s to develop ImT, such as virtual reality (VR), and diffuse them into the engineering workflow (Zaker and Coloma, 2018). However, only recently have improvements in hardware and software rendered the application of ImT viable and worthwhile (Miltiadis, 2015). According to Berg and Vance (2017, p.3), the current state of ImT in the A and C industry is “mature, stable and importantly usable”. Gartner’s hype cycle reiterates this and refers to the ImT as the “plateau of productivity” (Panetta, 2017). In various studies (Spaeth and Khali, 2018; Shi *et al*., 2019; Zhang *et al*., 2019; Lucas, 2018), it has been reported that ImT can be highly beneficial in design, construction and operational activities such as safety assessment, training, space planning, ergonomics and functional requirements, lighting design, interior design, evaluation of construction scenarios, facility management and so on. Thus, the application of ImT in the A and C industry belongs to a broad spectrum and the exciting opportunity for immersive visualisation and interaction offered by ImT has captured the attention of a growing number of researchers in the domain of Architecture and Construction. In several studies, various challenges faced by the A and C industry in mainstreaming ImT as an enhanced tool for improving productivity have been reported. However, currently, there has been no research in which these challenges have been integrated systematically and collectively. A systematic review in this area is highly critical, as it will assist in research, decision-making and policies by integrating critical information, as suggested by Mulrow (1994). Thus, the aim of this paper was to fill this gap by consolidating the challenges targeting the A and C industry by conducting a systematic review.

This study aims to fulfil the following objectives:

- To undertake an extensive review of previous studies that focuses on the application of ImT in the A and C industry.
- To present areas of research concentration and paucity in this field.
- To present a synthesis of the evidence available thus far on the challenges associated with the development and use of ImT within the A and C Industry.

The remainder of this paper has been organised as follows: Section 2 contains the background to the enabling technologies of ImT in the context of the A and C industry; Section 3 contains an explanation of the research methods involved in the systematic review; Section 4 consists of the summary and the interpretation of the results; and Section 5 concludes this study by listing out challenges, trends and recommendations for the future research direction.

3.2. Immersive Technology in the A and C Industry

Owing to its flexibility in being adapted to different problems and domains, ImT has evolved rapidly in recent years, which has led to different interpretations of a virtual environment (LaValle, 2016). The present state of ImT is built upon ideas that date back to the 1960s (LaValle, 2016). A vast variety of immersive technologies are used to create a virtual environment (VE), with various levels of immersion and capabilities (Lingard, 1995; Spaeth and Khali, 2018). These levels can be divided generally into three, as shown in Figure 3.1: a) Passive VE, b) Exploratory VE, and c) Immersive VE (Lingard, 1995; Spaeth and Khali, 2018). Passive VE refers to spectator activities such as watching movies and TV, which might also be referred to as a non-immersive system

(Mujber *et al*., 2004), whereas an exploratory VE involves exploring a 3D environment interactively through a 2D interface, such as a monitor (Lingard, 1995) which can be referred to as a semi-immersive system. Immersive VE refers to a synthetic environment where the user can interact fully with the artificial environment with all the senses being stimulated (Lingard, 1995). Therefore, in this study, only those immersive technologies which are capable of providing an immersive VE (Sharples *et al*., 2008; Feng *et al*., 2018), facilitated by a head-mounted device (HMD) or a projection-based display (PBD), are considered.

A variety of immersive VE enabling devices is used in present architecture and construction practice. HMD-based VR is one of the immersive technologies used widely in the A and C sector. HMD-based VR is used to facilitate a truly immersive environment, using a true, stereoscopic, 3D display projected onto both eyes of the users (Shen and Grafe, 2007; Setareh *et al*., 2005). Another type of immersive technology used in the A and C industry is the CAVE system, which has a large, stereo projection system that involves the use of light-weight polarising glasses (Kim *et al*., 2013). Mixed reality (MR) is another type of cutting-edge, immersive visualisation technology, which was recently embraced by the A and C industry (Guo *et al*., 2017). Unlike the HMD-based VR, which isolates the user from the real world and secludes the user in a purely synthetic world, MR involves the merging of the real and virtual world (Geroimenko, 2018). Thus, in an MR the 3D environment, computer-generated visual content is superimposed and anchored onto the real world to supplement the user's perception of the real world through an HMD device, such as the Microsoft HoloLens (Geroimenko, 2018). Therefore, mixed reality is a “reality spectrum” between pure “reality and pure virtual reality” (Milgram and Kishino, 1994). These Immersive VEs are capable of contributing several benefits, resulting from their application in the A and C industry and, presently, their application domain in the A and C industry is limitless. There are studies (Shi *et al*., 2019; Okeil, 2010; Gurevich and Belaciano, 2014) in which it has been suggested that integration of these Immersive VEs during the design phase of a project makes it possible to assess the functionality of space on a true scale by creating space in direct relation to the body, thereby bridging the gap that exists in the present building design process. Similarly, there are studies in which it has been identified that the use of Immersive VEs in architectural practice can dramatically reduce the time and effort required for design tasks through spatial interaction with models (Wolfartsberger, 2019; Sacks *et al*., 2013; Gurevich and Belaciano, 2014).

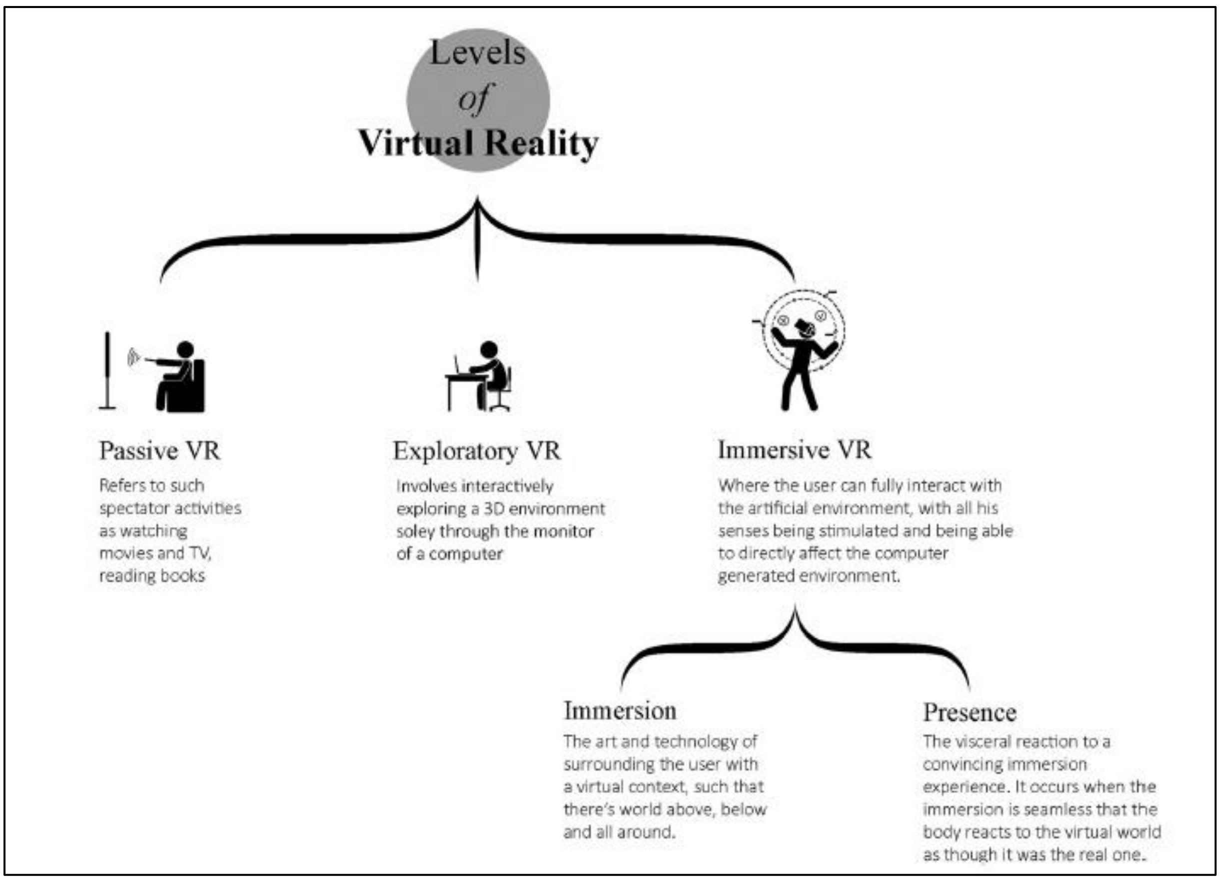

Figure 3.1: Levels of Virtual Reality (Spaeth and Khali, 2018)

During the design phase of a project, Immersive VE has been used as an effective tool in building mock-ups to analyse and address issues before the building is constructed (Dunston *et al*., 2011;

Gopinath and Messner, 2004; Majumdar *et al*., 2006). A one-to-one scale with an excellent sense of realism enables the immersive VE to provide an immersive virtual mock-up, delivering a better understanding of the project to its end-users and stakeholders, resulting in improved and enhanced communication. For this reason, the A and C industry has adopted ImT as a tool for collaborative design (Iorio *et al*., 2011) to facilitate an excellent avenue for information exchange in a multi-disciplinary environment (Rosenman *et al*., 2007;(Sydora, 2019). Furthermore, during the design phase of a facility, researchers have used Immersive VE as a medium to visualise and simulate building user interactions, route mapping within a designed environment (Simeone *et al*., 2012; Simeone *et al*., 2013), simulating user energy conception behaviour (Goldstein *et al*., 2011), and simulating crowd behaviour during emergency evacuations (Pan *et al*., 2007).

Similarly, ImT has been used to demonstrate effectiveness in construction safety training (Shi *et al*., 2019; Lovreglio *et al*., 2018; Cao *et al*., 2019; You *et al*., 2018; Ronchi *et al*., 1873; Saeidi *et al*., 2018; Andree *et al*., 2016) and other construction-related education (Shi *et al*., 2019; Vahdatikhaki *et al*., 2019; Wu *et al*., 2019; Sacks *et al*., 2013). The capability of ImT to be used to model human behaviour with a high degree of fidelity led Shendarkar *et al*. (2008) to suggest that ImT is an effective tool for conducting emergency management. Similarly, Smith and Ericson (2009) revealed that the enthusiasm of users for safety training skills could be enhanced by using Immersive VE to engage with their learning environment. A framework developed by Cheng and Teizer (2013) to visualise and simulate construction data for training construction workers is a key study on the application of ImT in the construction phase. Even though there are some gaps in linking ImT and the construction phase of a project, few efforts have been made, such as that of

Kamat and Martinez (2001), to study the possibility of simulating various construction equipment operations, to identify an optimal solution for construction activity planning.

The possibilities of ImT have been extended to the operational phase of a facility as well, which has quickly attracted the attention of the A and C industry. The real-time data capturing, visualisation and, importantly, interacting with that data are other functionalities contributed by ImT to this sector (Hailemariam *et al*., 2010; Malkawi and Srinivasan, 2005). This has led to the direct use of a virtual environment for planning and daily maintenance of a facility, offering efficient and timely access to information about a building through sensor data and by pinpointing malfunctioning equipment and systems (Frazier *et al*., 2013; Hou *et al*., 2014).

3.2.1. Commercially Available ImT Applications for A and C Industry

Digital transformation is shaping industries and changing the way humans work across many industries and the A and C supply chain is catching up with the growing popularity of technologies like ImT. Construction supply chain organisations like Caterpillar group, 3M, Hilti, and ITI VR have already capitalised on the use of ImT to optimise construction-related activities such as earthmoving operations, safety training, work inspection, logistic planning, design communication and risky equipment training simulations for equipment like cranes. Liao *et al*., (2021) suggest that human error or unsafe behaviours contribute to 90% of construction accidents. In this context, the relevance of utilisation of immersive technology for construction-related training by the construction supply chain cannot be overemphasised considering the fact that ImT provides a new opportunity for effective training and education with a higher level of cognition which is impossible to achieve using conventional training methods (Li *et al*., 2018). Similarly, ImT has been widely used in the A and C industry for risk-prone equipment operations. One of the examples of such a commercially developed VR system is the ITI VR (ITI, 2022) which utilises ImT for overhead crane operator training. Poovladvand, (2021) reiterates the effectiveness of ImT-based system training systems for complex and risky equipment operations such as the use of overhead cranes. Further, the utilisation of aerial surveillance using drones and ImT for construction activities such as site surveying, progress monitoring, work inspection, logistic planning and coordination and hazard identification has also gained momentum (Elghaish *et al.*, 2021). Gray, (2022) suggests that utilisation of ImT integrated drone surveillance can enhance safety managers' efficiency by 50%. Since the seminal work by Schön, (1988), it has been widely acknowledged that stakeholders and designers occupy an entirely different design world making design communication more challenging. Through the utilisation of ImT, major construction contractors like AECOM, and Balfour Beatty, UK are also reaping the benefits of immersive visualisation and interactivity functionality offered by ImT to communicate its design to the stakeholders effectively, delivering a true sense of the scale and presence. Cumulative evidence suggests that as ImT continues to improve, its viable commercial use-cases are beginning to emerge. It is worth noting that while there exist a plethora of commercial VR systems, there is a need to explore empirical evidence of the impact and issues associated with their use in practice. One way of achieving this is to thoroughly interrogate published and peer-reviewed publications that have investigated the use of ImT in the A and C contexts.

3.2.2. Challenges Posed by Immersive Technology in Architecture and Construction

There is no denying that ImT possesses huge potential for boosting efficiency in the Construction Sector. Cumulative evidence has indicated the potential of ImT to provide a strong sense of presence (Hoffman *et al.*, 2003) that can trigger natural human behaviour, similar to the physical world (Heydarian *et al*., 2015). As a result of this potential, ImT is considered to be an extremely promising tool for improving the process of architecture and construction workflow (Fernandes *et al*., 2006; Messner *et al*., 2003; Rekapalli and Martinez, 2007; Park and Kim, 2013). Despite the enthusiasm and hype surrounding the applications of ImT in the A and C industry, there is a substantial gap between the technology that is readily available and the technology that is needed to realise the full potential of ImT systems envisioned in various domains of application in architecture and construction. A substantially improved system is imperative for any technology, such as ImT, to be truly successful and widely adaptable throughout the industry. Therefore, it was imperative to evaluate the current state of the art in the field of architecture and construction systematically to understand the challenges posed by mainstreaming ImT into architecture and construction practice and to suggest how future objectives in this area might be pursued.

3.3. Research Methodology

To achieve the objectives of this study, a systematic review was conducted to explore comprehensively the challenges faced in embracing ImT into the workflow of the A and C industry. Qualitative data analysis was carried out to identify empirical evidence of the challenges posed by ImT. The qualitative systematic review helped to identify findings from various studies on the chosen subject, which helped to accrue a high level of conceptual or theoretical development and achieve a greater understanding beyond what could be achieved through an independent study (Campbell *et al*., 2003). The challenge was to analyse the literature in detail, preserving the individual integrity of each study, without being overwhelmed by detail to produce a usable synthesis (Sandelowski *et al*., 1997). The research for this study was divided into the following stages: a) Identification of journals b) Review of journals c) Definition of classification framework

d) Classification of journals based on the framework.

3.3.1. Identification of Journals

Inclusion/exclusion criteria were developed to identify suitable literature for review based on the two key questions highlighted by Meline (2006, p. 22): a) Is the study relevant to the review's purpose? b) Is the study acceptable for review? Chambers (2004) pointed out that reliable inclusion/exclusion criteria are the key elements for a high-quality systematic review, even though a large proportion of the literature (90% or more) might be excluded from the study.

3.3.2. Inclusion/Exclusion Criteria

Below are the inclusion/exclusion criteria, based on which suitable literature was identified:

- Articles published between 2010 and 2019 (inclusive) were considered to maintain currency. Since ImT is an emerging development, which is subjected to constant evolutions and refinements, it was imperative to review recent literature to maintain the reliability and currency of the findings, as proposed by Meline (2006).
- Only literature referring to Immersive VE was considered to be eligible for this study. As discussed earlier, other forms of virtual environments, such as passive VE and exploratory VE, which do not provide users with full immersion, were not considered to be eligible for this study and were excluded.
- To maintain a predetermined threshold of quality, only rigorously peer-reviewed journals were considered for this study. Conference papers, book chapters or non-international

journals were excluded, thus satisfying the best-evidence principle proposed by Slavin (1986). The non-inclusion of grey literature resulting in publication bias might be considered to be a limitation of this study, but the rationale was solely a trade-off between selecting high-quality literature and the inherent risk of broadening the information bias that must be anticipated when a study of doubtful reliability is included.

- Literature in which theory, concepts or proposals are discussed only, without following any experimental testing or case studies was excluded from this study. The development and implementation process of any Immersive VE is a critical element in identifying the challenges faced when diffusing such developments into architecture and construction workflow. Thus, only literature that was focused on development and validation was considered to be eligible for this study.

3.3.3. Literature Identification Process

A four-stage approach, shown in Figure 3.2, which is built upon the preferred reporting items for systematic literature review and meta-analysis (PRISMA) framework (Moher *et al.*, 2009) was adopted and the inclusion-exclusion criteria were applied to identify relevant literature for this study. Stage One of the process involved a rigorous search of the relevant databases. It has been suggested in various studies that a minimum of two databases must be considered in a literature search for a systematic review (Levy and J. Ellis, 2006; Vom Brocke *et al.*, 2009; Thome *et al.*, 2012; Thome *et al.*, 2016).

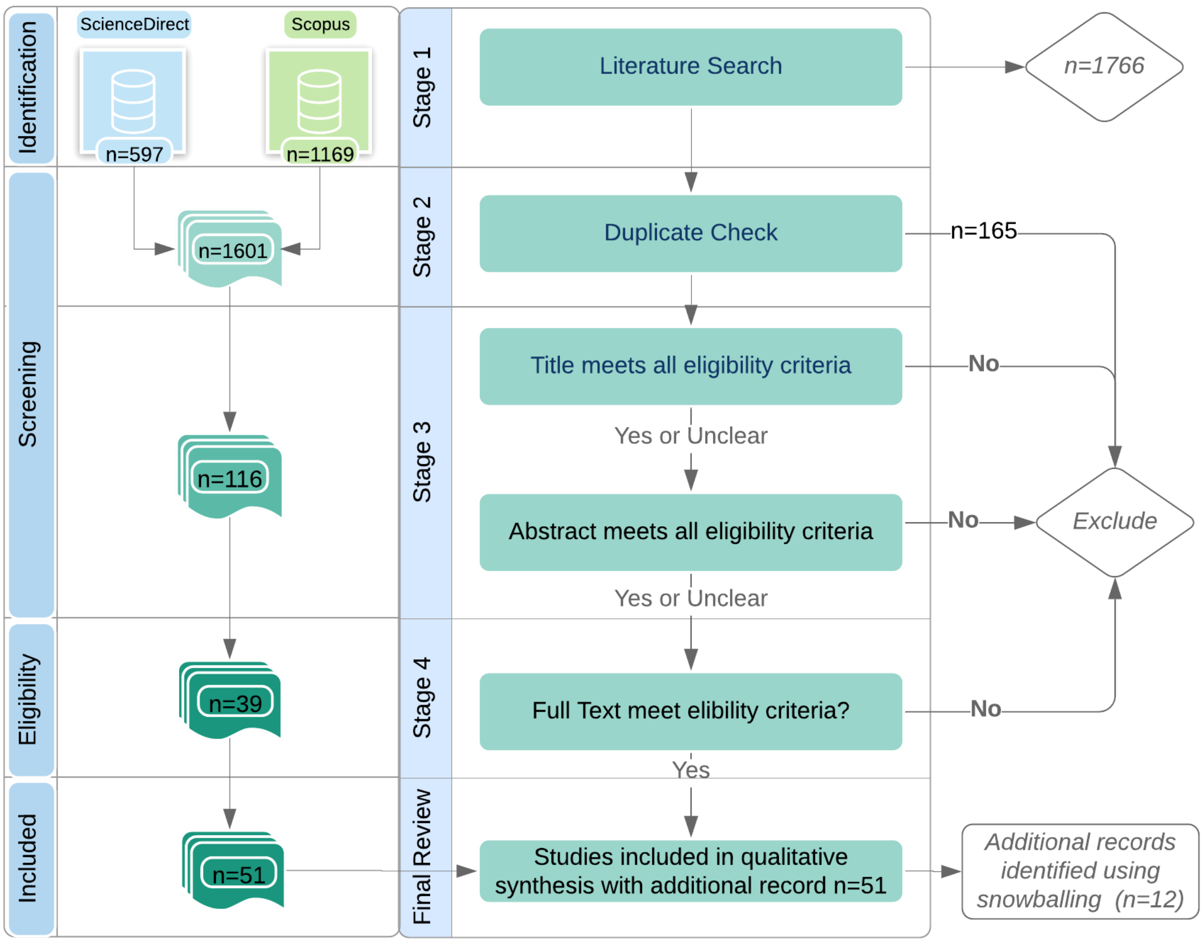

Figure 3.2: Literature selection process (author's own)

Two prominent databases (Scopus and Science Direct) within the domain of construction engineering and management were chosen for the literature search. Scopus is one of the largest abstract and citation databases of peer-reviewed literature, with nearly 27 million abstracts, 230 million references and 200 million web pages (Xiao et al., 2022).Similarly, Science Direct is another world-leading database, covering 12 million publications from 3500 academic journals and 34 000 books, consisting of scientific and medical research (ScienceDirect, 2019). The keywords used to search the literature within the scope of this study were:

("Immersive Technology" OR "Virtual Reality" OR "Mixed Reality" OR "Augmented Reality" OR "Digital Reality" OR "CAVE Automated System") AND ("Construction" OR "AEC" OR "BIM" OR "Built Environment" OR "Architecture").

In the keyword search, augmented reality (AR) was deliberately included. It ought to be noted that, even though AR by its definition is not an ImT (Gao *et al*., 2019) and does not meet the inclusion/exclusion criteria, some studies have represented immersive MR as AR (Woodward *et al*., 2010; Dunston and Wang, 2011). Therefore, in the search criteria, AR was added to maintain inclusiveness, and the literature which did not satisfy the definition of immersive MR (Milgram and Kishino, 1994) was filtered out in Stage Three (title and abstract review) of the study. Thus, a broader keyword search was used, as recommended by Cooper (2015), in order not to restrict the amount of literature artificially, but to elicit only those studies that were relevant to the research topic. Similarly, Hosseini *et al*. (2018) also emphasised the importance of using a broader keyword search for inclusiveness. In addition, backward and forward snowball search methods were also used as a means of retrieving relevant literature. Greenhalgh and Peacock (2005) recommended backwards and forward snowball searches as an effective method of identifying literature and maintaining inclusiveness. The search resulted in the retrieval of 1169 literature from Scopus and 597 literature from Science Direct.

Stage Two of the process involved screening for duplication, where duplicate literature (which is common in search results) was removed. This process was carried out at this early stage because the inclusion of duplicates in later stages could lead to double counting of data, resulting in bias as well as leading to unnecessary additional screening efforts. Microsoft Excel's duplicate removal function (Microsoft, 2019) was used for the duplicate screening process. A total of 165 duplicate files were identified and removed at this stage, resulting in a total of 1601 literature being moved to Stage Three of the process.

In Stage Three, an abstract and title review was performed and only literature that dealt strictly with Immersive VE technologies in the A and C industry was considered. Literature that was inconclusive in the abstract regarding the technology used was cleared for Stage Four (full-text review) and excluded if the criteria were not met. This stage of the process yielded 116 literature that was eligible for the final stage.

In Stage Four, a full-text review was performed, and 39 literature were identified as being eligible for qualitative synthesis for this study. Further snowballing was adopted to identify an additional 12 pieces of literature that were eligible, through a forward and backward search in Google Scholar. The same inclusion and exclusion criteria were applied to the literature identified through snowballing. Finally, 51 literature (n = 39 from the database search and n = 12 from snowballing) were identified as being eligible for the qualitative synthesis of this study, as shown in Table 3.1 and Figure 3.3.

Table 3.1: Number of articles by journal and year of publication

	Total	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Automation in Construction	17					1	1		2	5	8
Computers, Environment and Urban Systems	1						1				
Advanced Engineering Informatics	1									1	
Computers in Human Behaviour	1										1
Journal of Cultural Heritage	1										1
Alexandria Engineering Journal	1										1
Universal Access in the Information Society	1										1
Journal of Information Technology in Construction	2	1								1	
Buildings	1									1	
International Journal of Architectural Computing	2							2			
IEEE Transactions on Visualization and Computer Graphics	1										1
Lighting Research and Technology	1										1
Computer in Industry	1	1									
Electronic Journal of Information Technology in Construction	1		1								
Computer Application in Engineering Education	1									1	
Multimedia tools and application	1									1	
Construction Management and Economics	1				1						
Architectural Engineering and Design Management	1									1	
Computer Animation and Virtual Worlds	1										1
Sustainable Cities and Society	1										1
Fire and Materials	1							1			
Journal of Computing in Civil Engineering	4						2	1	1		
Journal of Transportation Safety and Security	1							1			
Presence: Tele-operators and Virtual Environments	1									1	
Journal of Construction Engineering and Management	2									1	1
Virtual Reality	1	1									
Visualization in Engineering	3							1	1	1	
Total	51										

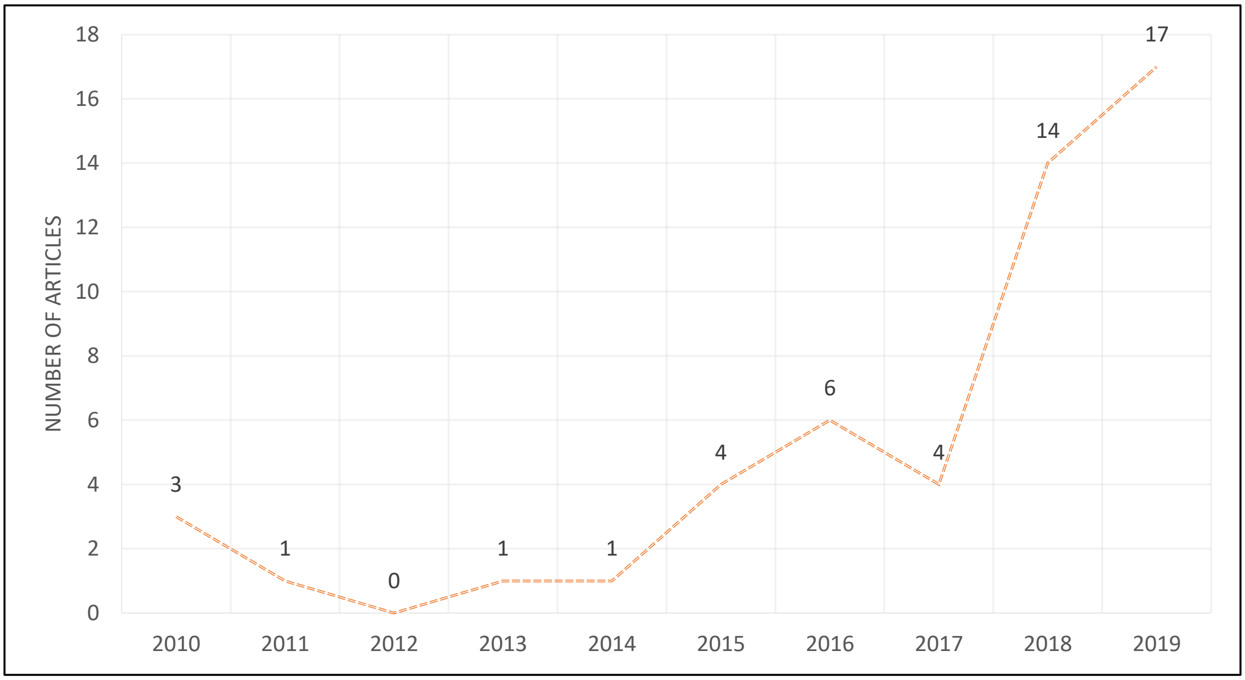

Figure 3.3: Yearly publication from 2010 to 2019

3.4. Framework for Classifying Literature on ImT in the A and C Industry

To comprehend and further segregate the eligible literature effectively, a classification framework was developed based on the grounded theory method (Glaser and Strauss, 2017), which consists of the dimensions and categories shown in Table 3.2. A classification framework for categorising literature about ICT, based on grounded theory, has become an emerging methodology as noted by Urquhart *et al*. (2010). Therefore, this methodology was found to be suitable for this study.

Table 3.2: Dimensions and categories of the literature classification framework

Dimensions	Categories
Improvement Focus	Architecture and Design; BIM; Facility Management; Safety Training; Construction Equipment Training; Construction Education
Research Method	Case Study; Experimental; Proof of Concept; Literature Review; Survey; Interview.
Users	Designers; Contractors; Client/End-user.
Technology Applied	VR; CAVE; MR
Project Phase	Concept Design; Developed Design; Technical Design; Construction; Operation
Maturity of the System	Framework; Prototype; Application Development;
Collaboration and communication in a virtual environment	Multi-User/Networked System
Focus on the sense of Presence	Boolean (Yes/No)
Sense of presence Enhancement focus	Visual; Haptic; Auditory; Olfactory; Interaction
Utilization Area	Progress Review; Design visualization/coordination; Defect Detection; Model Validation; Simulation; Virtual Prototyping; Education; Remote communication/collaboration
Challenges	Algorithm Development; Virtual Content Modelling; Interoperability; Infrastructure; Skills Availability; Cost; Ethical Issues; Multi-sensory Limitations; General Health and Safety;

3.4.1. Mapping of Journal Sources

Scientometric analysis was used to identify journal sources that published research based on ImT in the A and C sector. A total of 26 journals (Table 3.1) met the threshold when the minimum number of citations and the number of documents were set to 7 and 3 respectively. The nodes of these journals and their inter-relation are shown in Figure 3.4, using connecting lines. According to the nodes and the font size shown in Figure 3.4, the most influential journals that had been contributing

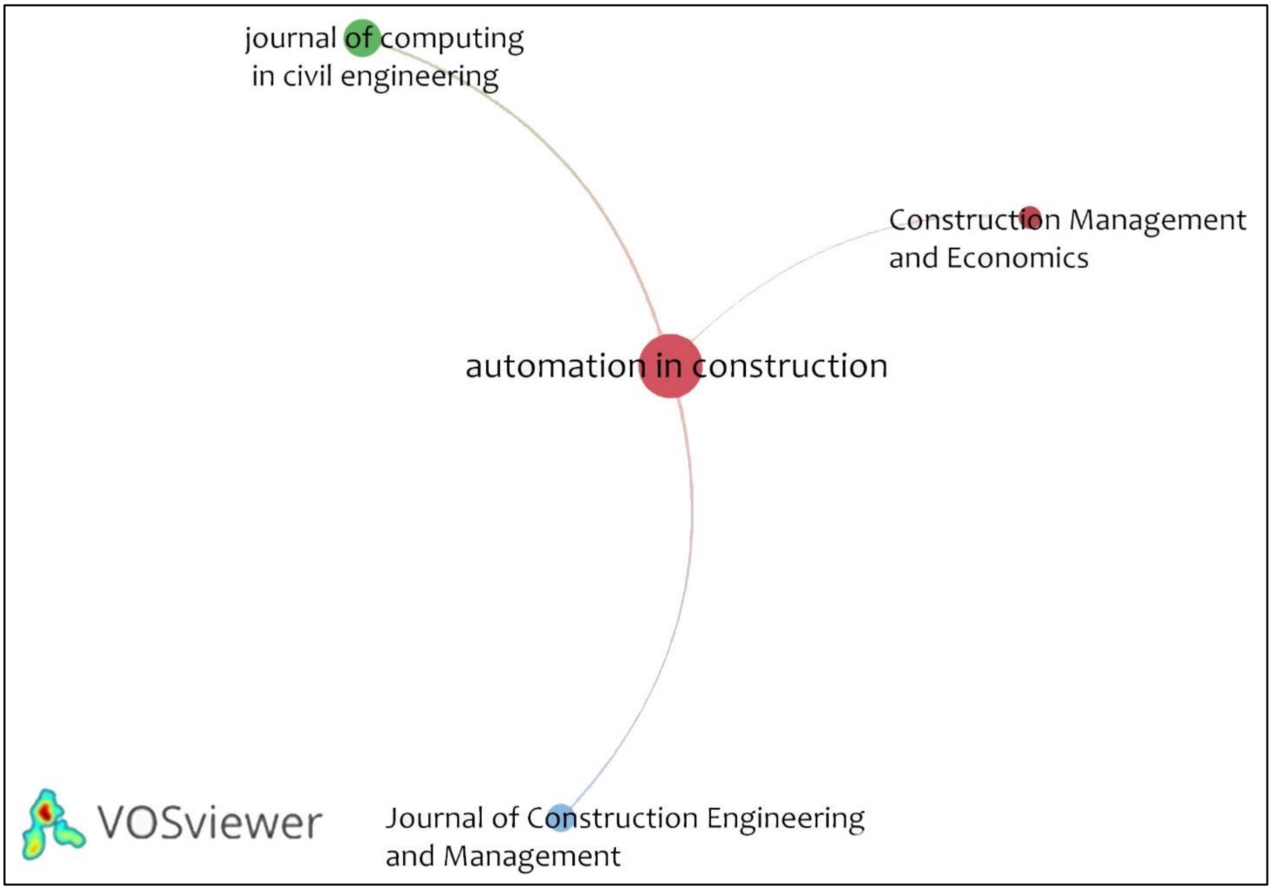

Figure 3.4: Mapping mainstream journals in the area of immersive technology in the A and C industry

In the research area of ImT application in the A and C industry were: Automation in Construction (AIC), Journal of Computing in Civil Engineering, and Journal of Construction Engineering and Management. The mutual citation among these journals is represented by the connecting lines and the clusters shown in Figure 3.4. An inter-relatedness among the journals was revealed through this mutual relation, which meant that the likelihood of one journal disseminating research outputs about the application of ImT in the A and C industry was based on the relevant findings from the other journal.

3.4.2. Co-Occurrence of Keywords

Sue and Lee (2010) suggested that keywords can be used to provide a clear and concise description of the research content. Furthermore, a network of keywords can be used to depict the knowledge existing between their relationship and the intellectual organisation of the research topic, as noted by Van Eck and Waltman (2009). “Author Keywords” and “Fractional Counting”, were used in VOSviewer, as proposed by Hosseini *et al*. (2018), for keyword filtering which yielded 11 keywords that met the threshold. Further, keywords, such as “survey, immersive, office buildings and virtual reality” were removed and keywords that shared the same semantic meanings (e.g., BIM and Building Information Modelling) were identified, resulting in a total of 9 keywords (Figure 3.5).

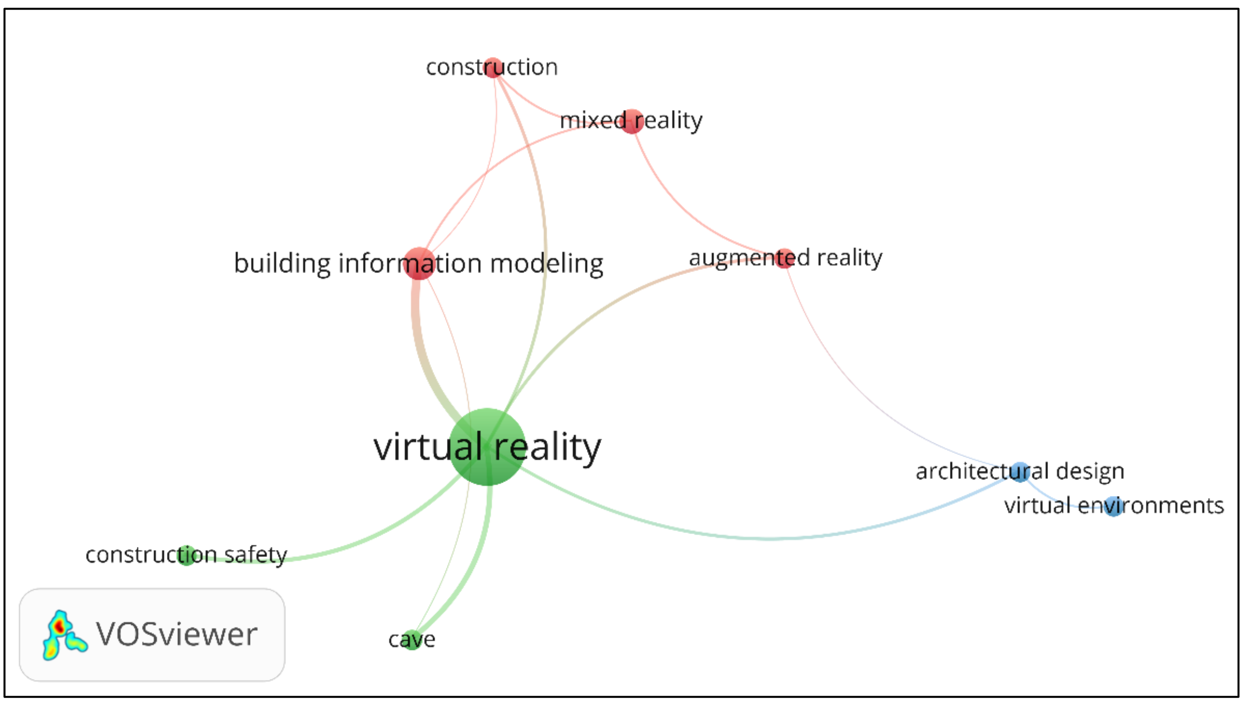

Figure 3.5: Network of co-occurring keywords in the research of ImT in the A and C industry

The node size, distance and connecting line between the keywords which are frequently studied (Table 3.3) are a clear indication of the strong connection between them. Further, each cluster in Figure 3.5 is presented in various colours and keywords within the same cluster are closely linked to each other.

Table 3.3: Summary of main keywords in ImT-based research in the A and C industry

Keywords within ImT in A and C	Total Link Strength	Occurrence	Average Year Published	Average Citation	Average Normalized Citation
Virtual Reality	13	24	2017	12.38	1.14
Construction Safety	2	3	2017	27.33	0.33
Building Information Modelling	6	6	2017	13.83	1.16
CAVE	3	3	2014	9.33	1.97
Augmented Reality	3	3	2014	17.67	0.82
Mixed Reality	3	4	2016	8	1.01
Construction	3	3	2016	20	1.13
Architectural Design	3	3	2014	30	1.15
Virtual Environment	1	3	2013	19.67	1.42

3.4.3. Citation of Articles

Articles with a high number of citations were identified using VOSViewer (Figure 3.6) by setting the minimum citation number to 10, yielding 6 articles that met the threshold.

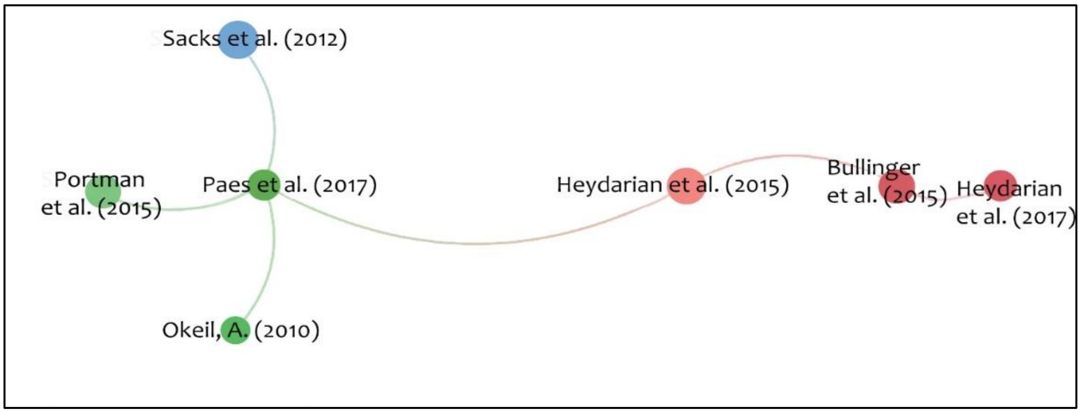

Figure 3.6: Network of highest-impact publications in ImT-based research in the A and C industry

Table 3.4 contains a summary of the list of publications with the highest impact on ImT in the A and C industry.

Table 3.4: List of publications with the highest impact on ImT-based research in the A and C Sector

Author	Title	Citation	Normalised Citation	Improvement Area	Technology Used
Sacks *et al*. (2012)	Construction safety training using immersive virtual reality	82	1	Safety Training	VR
Heydarian *et al*. (2015)	Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations	75	2.31	Arch. and Design	VR
Portman *et al*. (2015)	To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning	47	1.45	Arch. and Design	VR
Bullinger *et al*. (2010)	Towards user-centred design (UCD) in architecture based on immersive virtual environments	43	2.02	Arch. and Design	VR
Paes *et al*. (2017)	Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems	24	1.52	Arch. and Design	VR
Heydarian *et al*. (2017)	Towards user-centred building design: Identifying end-user lighting preferences via immersive virtual environments	19	1.12	Arch. and Design	VR

3.5. Summarising the Evidence

3.5.1. Classification of Articles with a Focus on Improvement

Articles were grouped into five categories based on the improvement that would occur as proposed in the article: (1) Architecture and Design; (2) BIM; (3) Facility Management; (4) Safety Training; (5) Equipment Training. As shown in Figure 3.7, 36% of the articles were focused on improving architecture and design practice and the principal focus of 33% of the articles was on improving the BIM process through the integration of ImT.

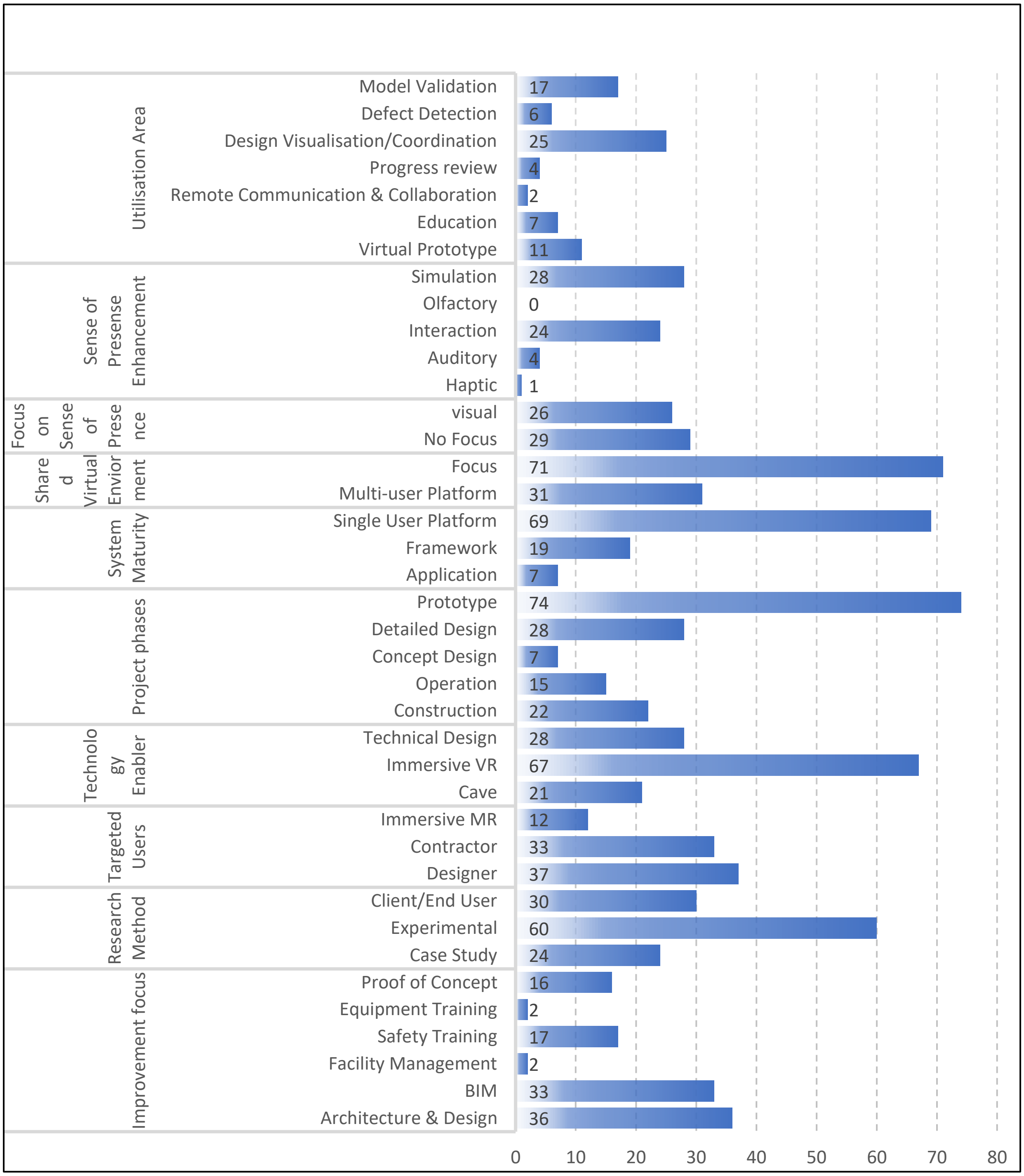

Figure 3.7: Number of articles based on the classification framework

A further 17% of the articles were focused on improving construction safety, and 2% of the articles were focused on equipment training and facility management using ImT.

3.5.2. Classification of Articles Based on Research Methodology

The articles were classified further into three groups (Figure 3.7) based on the research methodology adopted in the studies: (1) Case Study; (2) Experimental; (3) Proof-of-Concept. Literature, in which only theory, concepts or proposals were discussed without following any experimental testing or case study, was excluded from this study. The development and implementation process of an immersive environment is a critical element in identifying the challenges faced by such developments for diffusing into architectural and construction workflow. Thus, literature that were focused on development and validation was considered to be eligible for this study. The results showed that an experimental method was used to develop research in 60% of the articles, a case study method was used in 24% of the articles and proof of concept was used in 16%.

3.5.3. Classification of Articles Based on the Targeted User

Owing to the complexity and collaborative nature of the A and C industry, the beneficiaries of ImT in the construction industry were categorised into three: (1) Designers; (2) Contractors; (3) Clients/End-users. Articles that had a principal focus on enhancing or improving the workflow of any of these audiences were classified under the relevant user category. It ought to be noted that some of the articles targeted more than one user category and they were classified accordingly under multiple categories. The results (Figure 3.7) indicated that 37% of the articles targeted designers, 33% targeted contractors and 30% at clients/end-users.

3.5.4. Classification of Articles Based on Types of Immersive Technologies

Immersive technology, which typically isolates the user from the real world and is capable of providing a strong sense of presence for the user, makes it harder to differentiate between the real and the virtual world. For this study, only those devices which could provide such an experience for the user were considered. The articles were classified (Figure 3.7) based on the type of ImT used for the research. The majority of the articles (67%) used VR, a CAVE automated system was used in 21 % of the articles and mixed reality technology was used in 12%.

3.5.5. Classification of Articles Based on the Project Phase

In a construction project, various sequences of steps or project phases constitute the entire life cycle of that project. These stages can be categorised as: (1) Concept Design; (2) Detailed Design; (3) Technical Design; (4) Construction; (5) Operation. ImT was applied mostly in technical design and detailed design (28%), (22%) in construction, (15%) in operation, and (7%) in concept design (Figure 3.7).

3.5.6. Classification of Articles Based on the Maturity of the System

The articles were grouped further into three categories based on the stage of maturity: (1) Framework; (2) Prototype; (3) Application. The results (Figure3.7) showed that the principal focus of the highest number of articles was on developing prototypes, followed by the framework (19%) and fully developed application (7%).

3.5.7. Classification of Articles with a Focus on Communication and Collaboration in the Virtual Environment

The articles were classified also based on their focus on the use of the distributed virtual environment for remote collaboration and communication. Through the use of the distributed system, geographically dispersed users are able to connect in a shared virtual space, where interaction between the users and the shared world is possible (Gupta and Sharma, 2009). Effective communication and collaboration are key elements in the successful completion of any construction activity. This dimension of the framework was used to measure the number of articles in which the research was focused on the use of the distributed virtual environment. Surprisingly, in this category, the focus of a large portion of the articles (69%) was on the integration of a single-user platform (Figure 3.7) and the focus of only 31% was on the use of a multi-user virtual environment for communication and collaboration.

3.5.8. Classification of Articles with a Focus on the Sense of Presence

A high sense of presence has proven to be an integral part of an effective virtual environment (Lorenz *et al*., 2018). The importance of the sense of presence in enhancing the experience and efficiency of task-based activities in the virtual environment has been suggested in various studies (Lorenz *et al*., 2018; Cooper *et al*., 2018). Therefore, this dimension of the classification framework was used to categorise the literature based on whether it was focused on enhancing the sense of presence (Figure 3.7). Additionally, if there was any focus in the literature on enhancing the sense of presence, another classification (sense of presence enhancement) was used to identify the areas of improvement which was divided into five categories: (1) Visual; (2) Haptic; (3) Auditory; (4) Olfactory; (5) Virtual Interaction (Human-Computer Interaction). These multimodal cues are critical in supporting performance and improving the user experience and efficiency of the task in the virtual environment (Cooper *et al*., 2018). Typically, in an immersive virtual environment, stimulation relies mostly on visual cues (Cooper *et al*., 2018). However, factors such as frame rate, visual depth cues, display resolution etc. could have a huge impact on the sense of presence (IRIS VR, 2018). In this context, it must be noted that the aim of classification based on a visual cue was to identify the literature that was considered for enhancing the visual cues.

Improving various sensory cues was considered in a large percentage of the literature (71%), whereas there was no focus on the sense of presence enhancement in 29% of the literature. In most of the articles (26), enhancing the visual cues was considered, followed by 24 articles that were focused on enhancing natural interaction with the virtual environment and four articles that were focused on enhancing auditory cues. Only one article was focused on enhancing the sense of presence using haptic feedback, and none of the articles was focused on olfactory cues.

3.5.9. Classification of Articles Based on Utilisation Area

The area of application of ImT in the A and C sector belongs to a wide spectrum. In this section, the utilisation area of ImT was classified into eight categories: (1) Progress review; (2) Design Visualisation/Coordination; (3) Defect Detection; (4) Model Validation; (5) Simulation; (6) Virtual Prototype; (7) Education; (8) Remote Communication and Collaboration. The principal focus of most of the literature 28%) was on Simulation (Figure 3.7), followed by the use of ImT for visualisation purposes (25%). The focus of 17% of the literature was on the use of ImT for model validation, the focus of 11% was on virtual prototyping, 7% was on education and 6% on defect detection. The principal focus of less than 5% of the literature was on progress review and remote collaboration using ImT.

3.5.10. Challenges faced by the A and C industry in mainstreaming ImT

While there are several, clear benefits to using ImT in the A and C industry, there are many challenges to the mainstreaming of this technology (Messner *et al*., 2003). In this section, the literature was categorised based on the challenges reported during the research. Nine categories of challenges were identified: (1) Algorithm development; (2) Virtual Content Modelling; (3) Interoperability; (4) Infrastructure; (5) Skills Availability; (6) Cost; (7) Ethical Issues; (8) Multi-Sensory Limitations; and (9) General Health and Safety.

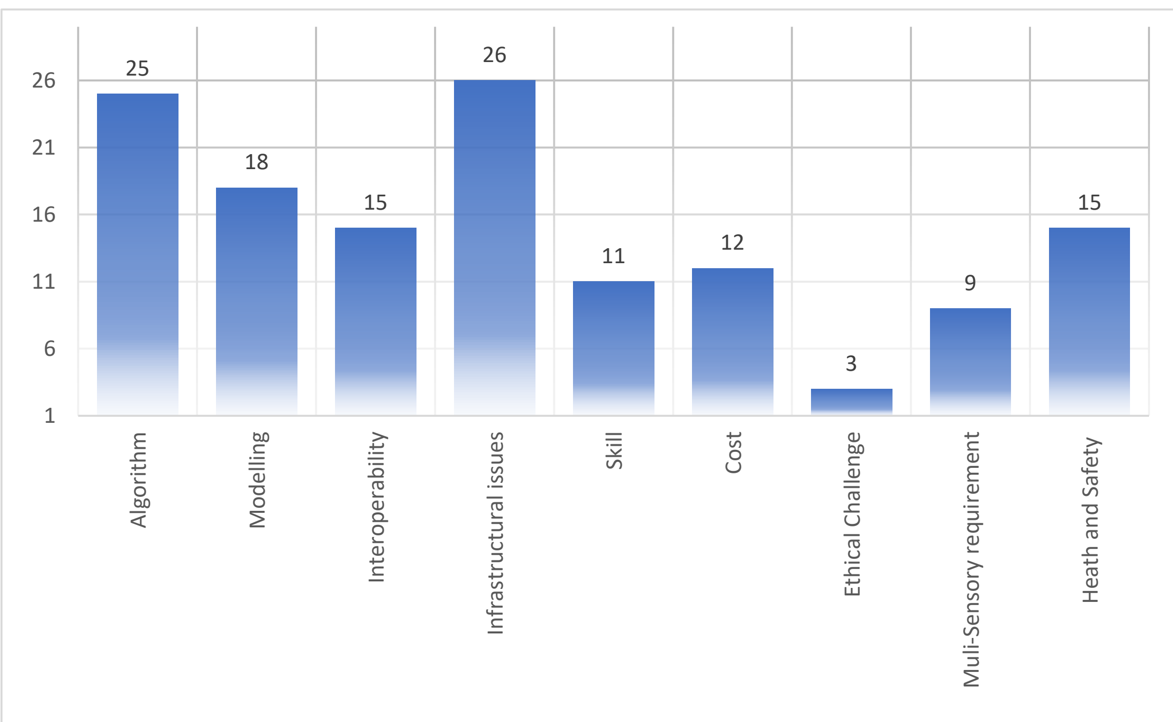

Figure 3.8: classification based on challenges

Figure 3.8 shows a summary of the challenges identified from 51, eligible, literature. Table 3.5 shows the theme of each challenge identified, and Table 3.6 presents the list of articles from which the challenges were identified.

Table 3.5: Challenges and themes

Challenges	Definition
Algorithm Development	Challenges associated with programming and the need to develop bespoke scripts that enables interaction and immersion suitable for A and C applications.
Virtual Content Modelling	Challenges associated with the development of virtual content to be used for immersive visualisation development.
Inter-operability	The capability of the various modelling tools used in the construction industry to exchange data into virtual environment development engines without undergoing multiple iterations.
Infrastructure	Issues that restrain the deployment of the virtual system due to the requirement of a dedicated space, hardware issues such as device weight, view angle, resolution, unrestricted user mobility, frame rate, portability, ease of deployment and device ergonomics.
Skill Availability	The lack of skill among construction professionals to develop and deploy an immersive virtual environment.
Cost	The cost incurred for software development including the purchase of development platforms, training, hardware procurement, and the space requirement for deployment.
Ethical Issues	Ethical issues including privacy, security, physiological, behavioural and cognitive impacts.
Multi-sensory requirement	Inability to incorporate multiple sensory modalities other than visual and auditory features to replicate the real-world experience.
General Health and Safety	Safety issues that may lead to accidents and ill-health including colliding with real-world objects, anxiety, eye strain, dizziness, nausea and electromagnetic exposure.

3.6. Discussion

A full range of articles, published in construction journals between 2010 and 2019 (inclusive), in which the application of immersive technology in the AandC industry was addressed, were reviewed systematically after a thorough search of key databases of research in architecture and construction. Based on rigorous inclusion and exclusion criteria, 51 eligible articles were selected for the final review. Predicated upon a wide range of scholarly journals, a generic taxonomy consisting of various dimensions was developed in this study. The eligible literature was classified and reviewed based on this taxonomy.

Table 3.6: Literature based on challenges

Literature	**Algorithm Development**	**Virtual Content Modelling**	**Interoperability**	**Infrastructure**	**Skill Availability**	**Cost**	**Ethical Issues**	**Multi-Sensory Limitation**	**General Health and Safety**
Shi *et al*. (2019)	√							√	
Rahimian *et al*. (2019)	√	√	√						√
Portman *et al*. (2015)						√	√	√	
Zhang *et al*. (2019)	√								
Lovreglio *et al*. (2018)	√			√					√
Vahdatikhaki *et al*. (2019)	√								
de Klerk *et al*. (2019)			√						√
Du *et al*. (2018)	√		√						
Heydarian *et al*. (2015)						√			√
Cao *et al*. (2019)		√							
Lee *et al*. (2019)		√		√					√
Chalhoub and Ayer (2018)		√		√					
Boton (2018)	√	√	√						
El Ammari and Hammad (2019)	√			√			√		
Wolfartsberger (2019)			√	√					
Bashabsheh *et al*. (2019)		√	√		√				
Wu *et al*. (2019)			√	√					
Lucas (2018)				√					√
Osello *et al*. (2018)	√	√	√					√	
Miltiadis (2016)	√			√					
Liang *et al*. (2019)	√			√				√	
Chen *et al*. (2019)				√					

Literature	Algorithm Development	Virtual Content Modelling	Interoperability	Infrastructure	Skill Availability	Cost	Ethical Issues	Multi-Sensory Limitation	General Health and Safety
Okeil (2010)	√			√					
Bullinger *et al*. (2010)									
Dunston and Wang (2011)	√			√				√	
Wang *et al*. (2018)	√	√	√						
Zaker and Coloma (2018)			√	√	√	√			√
Jutraz and Moine (2016)		√		√					
Ji *et al*. (2018)	√								
Heydarian *et al*. (2017)	√								
You *et al*. (2018)	√	√							√
Sacks *et al*. (2013)	√	√			√				
Gurevich and Sacks (2014)	√			√					
Spaeth and Khali (2018)		√		√	√	√			
Saeidi *et al*. (2018)	√			√				√	
Ronchi *et al*. (2019)				√		√		√	
Hilfert and König (2016)	√		√	√	√	√			√
Natephra *et al*. (2017)			√	√	√	√			
Hou *et al*. (2019)	√	√			√				
Andree *et al*. (2016)		√			√	√			
Zou *et al*. (2017)		√	√						√
Cosma *et al*. (2016)				√			√	√	√
Sacks *et al*. (2013)				√		√			√
Bosche *et al*. (2015)				√					
Ren *et al*. (2018)	√	√							
Paes *et al*. (2017)		√							√
Chokwitthaya *et al*. (2019)	√					√			
Wahlstrom *et al*. (2010)		√		√				√	
Hayden *et al*. (2014)				√	√	√			√
Du *et al*. (2017)			√	√	√	√			√
Wu *et al*. (2019)	√		√						

The findings of the review revealed that architecture and design as well as BIM have been the area with the greatest interest in ImT, being the focus of more than 63% of the literature. This was because immersive visualisation was first embraced in architecture and design, as architects are visually oriented and highly appreciate the requirement for visual cues to communicate their designs (Van, *et al*., 2012). Further, the findings revealed that, when compared with HMD-based MR and the CAVE system, HMD-based VR was used as the immersive technology in most studies. This was because, even though the concept of mixed reality could be dated back to 1994, the first, immersive, mixed-reality concept was actualised only recently, with the introduction of MR, head-mounted devices such as Microsoft Hololens (Microsoft, 2019). Owing to limitations in the field of view and rending quality when compared with head-mounted VR devices (Lang, 2019), MR technology might not be the first choice of architects and researchers for visualisation. On the other hand, a CAVE system can deliver high-quality visualisation, with possibilities of interaction (Ohno and Kageyama, 2007). However, the high cost, the complexity of the system and the space required to instal a CAVE system might have limited the interest among researchers and the weaknesses in the interactivity of the CAVE system, which is often spatially inaccurate and non-intuitive, have been noted in some studies (Havig *et al*., 2011). Several attempts have been made to develop low-cost systems (Mestre, 2017), resulting in poor visual and auditory immersion when compared with the original CAVE concept.

Similarly, the application of VR in construction safety training is a new area of interest for researchers. Training and experience are two key factors that can improve the ability of any construction worker to identify and assess risks (Sacks *et al*., 2013). However, the inefficiency of current training interventions has been identified in studies (Wilkins, 2011). This has prompted academic studies recently to explore the use of innovative intervention methods using VR. Compared with other immersive technology, such as MR and CAVE systems, VR has been proven to be a superior tool for construction safety training because it can seclude the user from the physical world completely, enabling a repeated experience of Spatio-temporal events which are sometimes impossible, dangerous and expensive to experience otherwise (Perez *et al*.,2007; Sacks *et al*., 2013). This has possibly influenced the increased reference to VR as an immersive technology in the literature related to construction safety. However, the possibilities of incorporating sensory stimulations other than visual and auditory cues are still an area of research that needs to be addressed (Gallace *et al*., 2012).

Inefficient communication among critical stakeholders is one of the major issues faced by the A and C industry. The recent development in ImT makes it possible to use shared or distributed virtual spaces, which enables users to communicate, interact and coordinate remotely. However, it was found in this study that most of the research (70%) was focused on single-user systems. The reason might be that the distributed virtual environment was still in its infancy and could cause major latency in information transfer because of network delays which have been noted as a major challenge in research studies (Morgan, 2005). These latencies in information transfer can adversely affect the overall user experience and decision-making capabilities in the virtual environment (Du *et al*., 2018). However, recent advancements in high-speed internet and the development of cloud-based, independent, network engines such as Photon (Photon, 2019) could alleviate these challenges, leading to many researchers focusing on this area.

The importance of the sense of presence in enhancing the efficiency of the task-based, immersive environment has been noted in various studies (Rose and Chen, 2018; Zimmons and Panter, 2003). It was found in this study that 70% of the literature was focused on enhancing the sense of presence, of which enhancement through visual cues and interaction was the main area of focus. This might be because the emergence of high-end hardware, software and game engines, such as

Unity 3D (Unity3D, 2019) and Unreal Engine (Unreal Engine, 2020), has eased the enhancement of visual cues, using a high-definition rendering pipeline (HDPR), and enabled interaction, which was a mammoth task otherwise. However, it was found also in this study that very few or no studies have focused on the integration of haptics and olfactory functionality in a virtual environment. This was probably because haptic and olfactory technology is still a research challenge, for which many researchers around the world were trying to identify an optimised system to replicate the natural sense of touch and smell.

3.6.1. Challenges that Restrain the Mainstreaming of ImT in the A and C Sector

The identified challenges were ranked based on the number of reported literature references and the utilisation area, as shown in Table 3.7 and Figure 3.9.

3.6.1.1. Infrastructure

In this review, it was found that 52% of the literature referred to infrastructural issues, such as device weight, display brightness, view angle, and device portability as the most critical challenges (Table 3.7 and Figure 3.9). Issues related to the weight of the device can have a negative impact on users' acceptance, which will restrain the wider adoption of ImT. In a study by Yan *et al*. (2018), it was suggested that the subjective discomfort of users and pressure load would increase as the weight of HMDs increases. The weight of HMDs has been associated also with the experience of visual discomfort and other injuries (Yuan *et al*., 2018). Similarly, it has been noted in various studies that display brightness (Vasylevska *et al*., 2019) and view angle (Arthur and Brooks, 2000) have a profound impact on the user's task performance as well as the level of immersion. However, it is noted that, with the advances of the recent chip revolution, HMD manufacturers are able to address these issues without compromising the processing capabilities and these challenges are expected to be alleviated in coming years (Metz, 2017).

Table 3.7: Ranking challenges based on utilisation area

	Progress Review	Design Visualisation/Coordinatio	Defect Detection	Model Validation	Simulation	Virtual Prototypes	Education	Remote communication /Collaboration	Mean	Median	Mode	Std-Dev	Mean Ranking
Algorithm Development	3	16	4	10	19	1	1	1	6.87	3.5	1	7.24	2
Virtual Content Modelling	2	10	2	9	10	3	1	0	4.62	2.5	2	4.27	5
Interoperability	4	11	4	8	6	2	3	1	4.87	4	4	3.31	3
Infrastructure	3	18	7	13	16	4	4	1	8.25	5.5	4	6.49	1
Skills Availability	3	9	3	6	5	3	3	0	4.00	3	3	2.67	7
Cost	2	11	2	8	6	3	3	0	4.37	3	2	3.66	6
Ethical Issues	1	1	1	1	1	0	0	1	0.75	1	1	0.46	9
Multi-sensory limitations	0	6	0	5	4	1	0	1	2.12	1	0	2.47	8
Health and Safety	3	10	4	9	5	3	4	0	4.75	4	3	3.28	4
Mean	2.33	10.22	3.00	7.66	8.00	2.22	2.11	0.55					
Median	3	10	3	8	6	3	3	1					
Mode	3	10	4	9	6	3	3	1					
Std-Dev	1.22	4.99	2.06	3.39	5.91	1.30	1.61	0.52					
Mean Ranking	5	1	4	3	2	6	7	8					

3.6.1.2. Algorithm development

In more than 50% of the literature, it was reported that developing an algorithm (scripting and programming) that will enable functionalities such as interaction and manipulation in the virtual environment is the second major challenge that could hinder the mass adoption of ImT by the A and C industry. This might be because, unlike in other industries such as the manufacturing and automobile sector, every construction project is unique, and the requirements of the stakeholders are different.

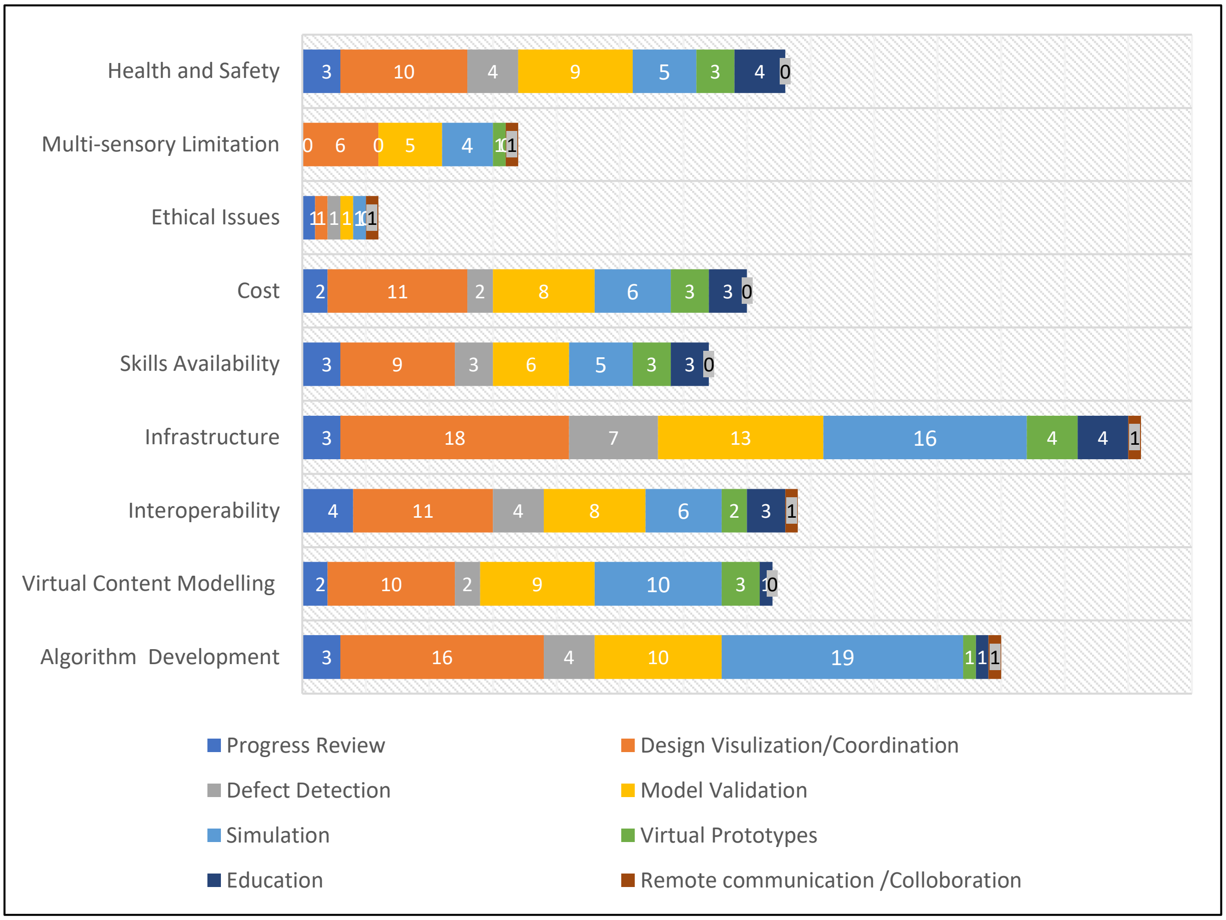

Figure 3.9: Thematic analysis of reported challenges

Therefore, to enable the virtual environment and the related functionalities to meet the stakeholders' requirements, each project requires tailored algorithms. Moreover, the development of a virtual environment that is interactive, informative, intuitive, immersive and illustrative requires specific development skills, referred to in 22% of the literature as one of the challenges. Any job or trade inevitably changes over time and the required skill sets are also subjected to change. With the A and C industry embracing a faster and more accurate process, there is a clear need for A and C professionals to stay up to date with programming skills. Over the years, there have been constant changes in the way A and C professionals work, and it is evident that this sector is very accepting of new and innovative methods. It is worth noting that architecture and construction curricula should include programming topics as a core subject to keep up with the demand of the jobs as well as the constant changes in technology. With the present shortage of skills throughout this industry (Liu *et al*., 2015; Sawhney, 1999), the A and C sector needs to attract a talented workforce to the industry. In the absence of this, the A and C industry will have to rely on third-party developers to deliver virtual content that might result in cost overruns.

3.6.1.3. Interoperability

Media and information-rich virtual environments have proven to be a help, as various construction stakeholders are able to comprehend the design effectively. However, the interoperability between the various construction design tools, such as Autodesk Revit (Autodesk, 2019), and VE development game engines, such as Unity 3D and Unreal Engine, is a major concern which is necessary to address so that the workflow of architecture and construction is streamlined (Rahimian *et al*., 2019). Recently, various software vendors, such as Unity (Unity3D, 2019), have made attempts to bridge this gap using middleware. However, these developments are still in their infancy and require further refinement and iterations using middleware applications. Furthermore, with the introduction of Unity Reflect (Unity Reflect, 2019), the transfer of BIM models, together with their meta-data, into the Unity game engine to enable an immersive experience has become easier. However, the challenge of creating interaction, which requires tailored algorithms, remains a challenge.

3.6.1.4. General health and safety

General health and safety issues associated with ImT, such as physical (hygiene, immersion injuries, unnatural postural demands), physiological (visual asthenopia symptoms, convergence cardiovascular changes) and psychological (stress, addiction, change in psychomotor performance), are major concerns while using these technologies (Costello, 1997). It is critical for any potential ImT user to choose the system based on the tasks and to understand the potential health and safety implications associated with the system. With the advancements in the quality of the display, such as OLED, locomotion techniques used, such as teleportation, light-weight hardware and wireless connectivity between HMDs and computers, it is expected that many of these issues could be mitigated. However, users should take great care to understand the manufacturer's recommended health and safety guidelines. Furthermore, a series of unwanted symptoms, such as nausea and headaches, are often the side effects of the immersive environment (Weech *et al*., 2018). Motion sickness caused by the virtual environment has been related in studies to various factors, such as frame rate drop and latency (Weech *et al*., 2019). However, with the advancements in software and hardware technology, as well as optimisation during virtual content development, these issues can be alleviated to an extent.

3.6.1.5. Virtual content modelling

To develop VR content that is truly engaging and compelling is a challenge that requires a considerable set of skills as well as resources. For those organisations that have adopted BIM workflow, this challenge might not be as critical as it is for other organisations that are still working towards BIM adoption. As discussed earlier, even though BIM models have to undergo several iterations before being imported into a virtual environment, the mammoth task of modelling the building can be done using BIM authoring tools as a part of BIM deliverables. As mentioned earlier, the latest software developments, such as Unity Reflect, enable users to import BIM models directly into the Unity game engine, even though they require post texturing, material enhancement and behaviour assignments, which are time- and resource-consuming tasks.

3.6.1.6. Cost

In this review, the cost was identified as one of the challenges that could restrain accessibility to ImT devices. This finding was reiterated in a study among construction professionals by Ghobadi and Sepasgozar (2020), who concluded that the high cost of peripherals is a major concern for the wide adoption of ImT across various industries. However, unlike CAVE systems which require huge capital investments for installation and maintenance (Manjrekar, 2014), in recent years, HMD manufacturers, such as Oculus etc., are able to bring affordable HMDs into the market (Coburn *et al*., 2017). However, it has been shown in studies that this pricing is the "tip of the iceberg" (Parrish, 2018) as these headsets require further investments in high-end computers that are capable of rending an experience that is richer and natural, which 52% of participants in a study by Parrish (2018) considered to be a major investment that would restrain the mass adoption of this technology. However, at one-tenth of the cost, the current generation of low-cost HMDs is approaching the capabilities offered by large, complex, ImT systems and, in the future, with the advancements in hardware and software technologies, these capability gaps are expected to shrink, further reducing the investments in processors for rendering experiences.

3.6.1.7. Multi-sensory limitations

Human beings perceive real-world experience through multi-sensory modalities often involving visual, auditory, tactile, olfactory, gustatory and, on some occasions, nociceptive (i.e., painful) stimulations (Gallace *et al*., 2012). Most enjoyable experiences of human life involve the stimulation of these senses (Gallace *et al*., 2012). However, thus far, immersive, virtual experiences have involved the stimulation mostly of visual and auditory senses. However, researchers (Gallace *et al*., 2012) have proved convincingly that increasing the number of sensory stimulations in the virtual environment can increase users' experience dramatically and, thus, the efficiency of the task. Although haptic and olfactory technology is in its infancy, once mature enough, these technologies will be highly beneficial for tasks that require touch and smell as factors in decision-making (Cooper *et al*., 2018). With advancements in technology, it is anticipated that multi-sensory suits (e.g., Teslasuit) will be used to overcome these challenges and introduce affordable technology into the market, which will assist greatly in the A and C industry in activities such as training, product selection etc.

3.6.1.8. Ethical issues

Ethical issues, such as prolonged exposure to the virtual environment resulting in users facing difficulties in performing normal tasks in the real world, as well as user privacy, were ranked as being the least reported challenge identified in this review. According to Moore's Law, there is a strong correlation between technological advancement and social and ethical impact (Moore, 2005). While the development of ImT applications is beyond simple entertainment, there has been much debate about the ethical complexities posed by the availability of new, low-cost, ImT devices (Jia and Chen, 2017). It has been noted in studies that these issues include physiological and cognitive factors as well as behavioural and socio-dynamic effects (Kenwright, 2018). Kenwright, (2018) suggested that this challenge could be overcome only through regulations and laws, such as governmental and institutional approvals, and through ethics-in-practice (respect, care, morals and education).

3.7. Conclusion and Recommendation

A systematic review was carried out to understand the challenges faced when mainstreaming ImT into the A and C industry. A structured methodology was used to identify 51 articles, published between the years 2010 and 2019 (inclusive), on the topic of ImT in the A and C industry from two predominant databases, namely: Scopus and Science Direct. Based on this study, it was identified that the most influential journals containing contributions to the research area of ImT applications in the A and C industry were: Automation in Construction (AIC), Journal of Computing in Civil Engineering, and Journal of Construction Engineering and Management. To comprehend and select the eligible literature effectively, a classification framework was applied based on the grounded theory method. In this review, nine categories of challenges were identified that might restrict the mass adoption of ImT in the A and C industry and these challenges were ranked based on the number of references to them reported in the literature.

Potential directions for future research have been identified in this systematic review. It is still necessary to investigate the impact of the various sensory modalities on improving the efficiency of the construction task in the virtual environment. Even though the multi-sensory requirement was considered to be a challenge in only 9 out of 51 literature sources, it is noted that, apart from the usual sensory cues (visual and auditory), very few or no sources were focused on incorporating other multi-modalities such as haptic and olfactory senses. In addition to this, measuring the success of the developed application must be validated by researchers from both academia and industry. The researchers assume that the ImT system will be assessed by the A and C industry, based on the contents, features and value for money. Therefore, any future research should be focused on developing ImT systems that are capable of synchronising project information, preferably in a real-time, user-friendly interface which can be easily diffused into the workflow of architecture and construction and, from a value perspective, can pay back the user in a shorter period. In this literature review, it was found that, in the present state of ImT, most of the system development was at a prototype or trial stage and therefore lacked the above attributes. However, since technology is in a phase of rapid evolution, it is highly recommended that industry partners monitor these developments closely and incorporate those which could bring value.

Chapter 4: The Effectiveness of Interactive Virtual Reality for Furniture, Fixture, and Equipment Design Communication: An Empirical Study

Abhinesh Prabhakaran[1], Abdul-Majeed Mahamadu[1], Lamine Mahdjoubi[1], Patrick Manu[2], Khairil Izam Ibrahim[3], Clinton Aigbavboa[4]

[1] Faculty of Environment and Technology, University of the West of England, Bristol, United Kingdom.

[2] School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, United Kingdom.

[3] Faculty of Civil Engineering, Universiti Teknologi MARA, Malaysia

[4] Faculty of Engineering and the Built Environment, University of Johannesburg, South Africa

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Statement of Contribution: This journal article is an empirical study which proposes a novel methodology for the development and testing of an interactive VR application for the FFE sector. My contribution as the main author of this article included conceptualisation, development of VR applications and implementation of the research and experiments, identification and synthesis of the literature, analysis and discussion of the results, draft and revise the paper based on the supervisors and reviewers' comments. Co-authors of this paper are my PhD research supervisors and collaborators who provided the mentorship, guidance, review of research concepts, methods and review of manuscripts. My overall contribution to this paper is estimated between 70-90%.

Abstract

This study proposes a novel approach to developing an interactive and immersive virtual environment for design communication in the Furniture, Fixture and Equipment (FFE) sector. The study further investigates its effectiveness in enhancing design communication and coordination between the stakeholders. Quasi-experimental research was adopted involving 12 FFE professionals, designers and end-users in a single-group pre-test-post-test design. The tests were performed primarily to ascertain the impact of the application of interactive Virtual Reality (VR) on delivering furniture design selection and coordination tasks. Further interviews were used to elicit participants' views on the functionality and usefulness of the proposed approach. Findings indicate that an interactive immersive virtual FFE environment: enhances the productivity of the design team through a collaborative virtual workspace offering a synchronised networked design testing and review platform; reduces the time required for the stakeholders to comprehend the design options and test those; enhances the design communication and quality of the design and encourages the collaborative culture in the industry; improves the design satisfaction of the stakeholders, and finally requires significantly less time for design decision making when compared to traditional methods. Future studies should incorporate space planning concepts and explore non-experimental methodologies in a real-life FFE project set-up. The proposed approach provides opportunities for enhanced interpretation of design intent in FFE as well as efficiency in design selection and coordination tasks when compared with conventional 2D methods of communication. This study proposes a step-change in the way furniture design is communicated and coordinated through an immersive virtual experience. Previous studies have not addressed the issue of impact on design coordination but instead focussed on marketing and sales.

Keywords: Virtual Reality, BIM, Furniture, Fixture and Equipment, Design communication

4.1. Introduction

The furniture, fixture and equipment (FFE) sector is a critical segment of the construction industry and remains the single greatest determinant of a building's day-to-day functionality which could conceivably influence the architectural aspects of a facility (Workspace, 2017). The importance of FFE in connecting the built environment, its occupants and the community is increasingly recognised. Studies (e.g., Ergan *et al*., 2019) have reported that people spend 90% of their time indoors, which highlights the significance of FFE and their effective arrangements in influencing human experiences in built spaces. Similarly, the contribution of FFE to the economy is also most noteworthy. This sector alone is estimated to contribute about £11 billion to the UK's GDP (The British Furniture Confederation, 2018). Like all other construction sectors, the FFE supply chain continues to face challenges that impede its competitiveness as well as performance (AMA Research, 2014; Renda *et al*., 2014). Other reports have reiterated performance decline in the sector, highlighting among other reasons, a lack of innovation and reliance on traditional workflows and methods across the delivery cycle (Družić, 2015). Thus, a design practice in the FFE sector continues to rely on traditional design tools and resultantly analogue means of design communication, leading to poor stakeholder engagement and satisfaction. According to Barbosa *et al*. (2017), the lack of innovation and resultant performance declines can be improved through the assimilation of digital processes into the FFE workflow including the adoption of Building Information Modelling (BIM) (NBS, 2016) and Immersive technology (ImT) (Garcia, 2017) in design as well as communication and marketing. Some studies suggest that inefficient communication arises among FFE's stakeholders due to current design practice attributing it to the inability of the stakeholders to interpret 2D designs leading to reworks, wastage and cost overruns (see Pakhale, 2020). Khanzode, *et al*., (2012) points out that this mode of design practice will lead to “redundancies, errors and omissions, duplication of information and efforts and difficulties in communicating the designs” with the stakeholders in an effective and timely manner.

It ought to be noted that the FFE sector’s designs are traditionally communicated to the stakeholders using two dimensional (2D) technical drawings, sketches and pictures (Cotey, 2017). Others rely on scaled-down physical prototypes which are costly and cumbersome to develop. Hall and Tewdwr-Jones (2010) report that communication issues that emanate between various stakeholders during the planning phase of a project are mainly due to the poor presentation and visualisation of the information. Studies (Biemans and Brand, 1995; Cotey, 2017) have reported, that through the adoption of BIM, the FFE sector is now embracing data-rich digital models to communicate their furniture designs. Similarly, the introduction of BIM into the FFE design workflow has enabled the placing of furniture, documenting and scheduling of the inventory more systematically and easier (Johnston, 2011). However, it could be argued that the sophistication of recent BIM models has reached an extent where it exceeds critical stakeholders' comprehension, limiting them from being effectively involved in the FFE layout development and reviewing of designs (Walasek and Barszcz, 2017) due to the so-called “black box effect” referring to a system lacking transparency and legibility for the participants (Rahimian *et al*., 2019). Thus, the previewing of such a data-rich three-dimensional (3D) model on a 2D interface such as paper-based or computer monitors still fails to convey the full depth of an intended design (Laval Virtual, 2017). A typical FFE product selection entails designers using a 2D or 3D FFE model prevailed on a 2D interface which can either be paper-based or a display followed by stakeholders reviewing those designs on a 2D interface. This process is still inefficient, although it could improve the productivity of this sector by enhancing the stakeholder’s understanding of the issues and design intent with a more shared understanding (Prabhakaran *et al*., 2018).

Rapid developments in ICT, especially immersive technologies i.e. virtual, augmented and mixed reality (VR/AR/MR applications), have offered new opportunities to address the communication and engagement gap in the FFE sector, which has offered a reliable extension of BIM for more advanced visualisation as well as communication (Rasmussen *et al*., 2017). Despite the potential of BIM-based ImT, there are few examples of their application within the FFE sector. Notwithstanding the well-documented potential of ImT in the FFE sector, reports have highlighted some limitations with current applications as merely an over-glorified extension of traditional 2D communications. Thus, the full potential of data-rich BIM models integrated with ImT has not yet been realised to its fullest extent. In bridging this gap, this study explores the effectiveness of an interactive immersive VR environment in enhancing the stakeholder's communication and resulting understanding of an FFE product design choice for a facility. The research thereof proposes a novel methodology for the development and application of a networked interactive virtual environment in FFE design communication.

The remainder of this paper is structured into eleven (11) parts. The first part (4.1) introduces the study where the motivation is indicated. The second part (4.2) provides an overview of immersive technology's application in the AEC industry. The third part (4.3) examines the decision-making behaviour in the FFE sector followed by the current state of immersive technology and BIM in the FFE sector is discussed in part four (4.4). In part five (4.5) we discuss the methodology adopted for this study and the virtual environment architecture. In part six (4.6) we discuss the details of data collection and analysis methods. In part seven (4.7) we detail the results of the experiment followed by a detailed discussion in part (4.8). Further in part nine (4.9), we provide an insight into the system design, architecture and procurement implication of the study results. In part ten (4.10) we highlight the limitations of this study followed by a conclusion in part eleven (4.11).

4.2. Immersive Technology in the AEC Industry

Recent improvements and widespread availability of hardware and software technology have contributed to making the use of immersive technologies more viable and worthwhile in the AEC sector Hosseini *et al*. (2018). Studies by Berg and Vance (2017) suggest that the current state of immersive technology is "*mature, stable and importantly usable*" in the AEC sector (p.3). Similarly, Gartner's hype cycle refers to the present state of immersive technology as the "plateau of productivity" (Panetta, 2017). Various studies have reported that immersive technologies such as VR and Mixed Reality (MR) can be highly beneficial in AEC activities such as design communication (Wolfartsberger,2019; Kang *et al*.,2010; de Klerk *et al*., 2019) and decision-making (Hartless *et al*., 2020), safety assessment and training (Getuli *et al*., 2020; Hilfert *et al*.,2016; Azhar, 2017), lighting design (Hong and Michalatos, 2016), interior design (Zhang *et al* 2019), evaluation of construction scenarios (Dawood *et al*., 2003), facility management (Shi *et al*., 2020) and so on. As a result of the successful development of applications in these fields, immersive technologies have captured the attention of a growing number of researchers in the AEC domain (Panetta, 2017).

For instance, de Klerk *et al*., (2019) used VR as a decision-making tool to assist architects during the early stages of ideation and design. This study, based on the user evaluation among both lay people as well as architects suggests that a VR system is a viable tool that can assist the architect in early-stage decisions, which is both easier, satisfying and more effective than CAD-based design tools. However, it ought to be noted that, the learning curve for both VR-based and CAD-based systems were identified to be similar. Also, the proposed system can only be used in the concept of ideation and decision making, as the system cannot provide accurate results as that of the CAD-based tools. In another study by Du *et al*., (2018) assessed the efficiency of VR as a collaborative decision-making tool through co-presences in the virtual environment as well as using a live BIM-metadata transfer protocol. This study revealed that co-presence can enhance the communication and decision-making process among the stakeholders and improve their level of presence in the virtual environment which reiterates the earlier findings of Saeidi *et al*., (2019). Furthermore, due to the limitations of the BIM authoring tool used (Revit) for this study, it was impossible to create a visually realistic environment that can deliver a compelling and richer experience for the users. However, it must be noted that earlier studies have pointed out that visual realism has a profound impact on the user's experience and decision-making (Padilla *et al*., 2018). With the recent development of highly efficient alternative tools (e.g. Enscape VR), it is now possible to have a live link between BIM models and the virtual environment without having to compromise the visual realism nor to have multiple iterations to achieve such realism.

In another study, Hartless *et al*., (2020) compared VR and AR technology to assess the behaviour of novice in making building design decisions on supporting wheelchair users. Using a counterbalanced approach with nineteen (19) participants, the authors measured the shift in perceptions of the participants while using two different technologies as well as used video recordings to understand the behavioural patterns of the participants during design modification and decision making in a VR and AR environment. The study revealed that physical exploration using both VR and AR not only delivered a novel design assessment experience but also had an

impact on the design decisions made by the participants. Chalhoub and Ayer, (2018) used MR to understand the impact on the productivity and quality of electrical conduit construction as well as to understand the performance of the users in MR when compared to 2D drawings. In a quasi-experiment conducted among eighteen construction participants suggest that MR enabled a significantly higher productivity rate, required lesser time to complete the task when compared to 2D-based tasks and lesser errors during the assembly task when compared to 2D-based tasks.
Further, with the advent of VR, a trend of capitalizing on the sophisticated VR application that can deliver a forgiving environment for visualising complex and risky workplace scenarios has also been witnessed. For instance, Getuli *et al*., (2020) in their study used VR and BIM to enhance the usual manual workspace plaining methodology by simulating the construction activity. A data collection through interviews and by analysing the position tracking, this study revealed the benefits in terms of the sharing of planning and safety-related information between stakeholders and its formal representation in the health and safety plan. VR's potential has also been tested in the context of spatial awareness. Lin *et al*., (2020) examined the effect of completeness of prior spatial knowledge in people's wayfinding behaviours during an emergency evacuation in an underground metro station using virtual reality technology. As evidenced above, several studies have explored the use of immersive technologies in the AEC in general. Despite its usefulness to the FFE sector, there is less research on its applicability and impact, especially as a decision support technology.

4.3. Decision-Making Behaviour in FFE

FFE plays a significant role in any facility which can constitute approximately 12% to 16% construction budget (Fidlschuster, 2007) and sometimes as high as 40% (i.e. in the health care industry which often has the highest budget for FFE products) of the overall construction budget (Fryer, 2012). Thus, FFE is a value driver that must not be underestimated, and attention to the minute design details is critical for successful project delivery (Fryer, 2012). FFE products are often purchased for appeal as well as function. Empirical studies have concluded that the design of an individual piece of FFE as well as how well it blends with a building's design and architecture has a profound influence on a client's decision-making behaviour (Pakarinen and Asikainen, 2001). The decision-making behaviour in FFE is a complex process involving the consideration of restraints such as cost, space availability and matching with the architectural aspects of the facility (Oh *et al*., 2004). Similarly, various studies have revealed that aesthetics plays a major role in the design choice of furniture (Sydora, 2019). Additionally, due to the significant expense and long product lifecycle of the FFE, clients have to make difficult trade-off decisions with regard to critical factors such as style and functionality (Oh *et al*., 2004). Thus, the end product of such a complex decision-making process is the uncertainty arising among the stakeholders over whether they have made the correct design choice. Hall and Tewdwr-Jones (2010) report that one of the greatest reasons for such uncertainties is the beneficiary's inability to comprehend the products in the facility for which those FFE elements are designed.

In this context visual representation using virtual reality plays a critical role in the FFE's design communication as well as the design decision process among the stakeholders as opposed to Roy and Tai (2003) and Yoon *et al*., (2010). The role of visualisation in decision-making has been emphasized and explored by many researchers. Yoon, (2010) used a web-based VR system to understand the decision-making behaviour in FFE. Despite the system being an exploratory VR, their study revealed that VR-based systems can highly assist decision-making while visualising FFE designs. Similarly, a study by Oh *et al*., (2004) using a web-based VR and conventional formats of two-dimensional design reiterates the finding of Yoon (2010). All these studies have undoubtedly concluded that, visualisation using virtual reality technology aid in understanding how well an FFE element blends with the architectural space and how well it serves the function of that space which has a greater impact on the client's decision-making behaviour. Further, Eppler and Platts (2009) reported visualisation using virtual reality in design decisions can alleviate the three main challenges (cognitive, social and emotional) posed by conventional methods of design visualization. Cumulative evidence reveals that virtual reality has great potential in assisting users during dynamic decision-making.

4.4. The Relevance of Immersive Technology and BIM in the FFE Sector

During the space planning phase of a facility, it is critical that all actors, understand, participate, communicate and collaborate to yield high-quality and optimised outcomes (Johansson *et al.*, 2014). Tantawy (2015) points out this process is critical as space is a precious and finite resource, which imposes a huge responsibility on the designers as the facility users will be spending most of their time on these FFE elements, and it should be functional, comfortable and pleasing as well as psychologically and visually pleasant and friendly. Recently, through the adoption of BIM, the FFE sector is now embracing data-rich digital models to communicate their furniture designs (Cotey, 2017). NBS (2016) defines BIM as the *"process for creating and managing information on a construction project across the project life cycle where the key output of this process is the digital description of every aspect of the built asset"*. A vast amount of data is embedded in BIM which makes it an excellent source for immersive simulation (Lin *et al.*, 2011). The latest technological advancement has facilitated a BIM-based game engine to stretch its possibilities for immersive environment development, providing opportunities to transform the FFE design and communication paradigm. FFE contractors are adopting this digital process as a means to compete in the actual furniture market, which has resulted in a competitive advantage in maximising product reach and client engagement.

The FFE industry is migrating from 2D design to data-rich 3D designs, which have enhanced the collaboration and permitted a better understanding of the design. This collaboration has extended beyond conventional human-human collaboration leading further into human-machine, giving birth to the concept of generative design and its application in space planning. While the concept of generative design is not new in the manufacturing sector, its implication in FFE design planning is gradually acquiring momentum in recent years. The integration and application of computational intelligence (CI) and artificial intelligence (AI) approaches with BIM for space planning has facilitated the automation of human tasks in the design and planning process, thus transforming BIM authoring tools into more intelligent and flexible than ever before (Racec *et al*, 2016). This intelligence and flexibility offered by metaheuristic search algorithms when integrated into BIM tools in the FFE design process are offering a new opportunity to FFE designers for testing a plethora of alternative designs which is impossible when done by human designers alone due to time and cost constraints (Racec *et al*., 2016). Many studies (e.g. Sydora, 2019) in recent years have focused on the integration of these metaheuristic search algorithms in capturing the interoperable relationship between an FFE design and its virtual spatial object representations in BIM, leveraging opportunities to create programming diagrams and adjacency studies on 3D FFE representations leading to the discovery of novel and high performing design results within a given design system.

Even though the well-recognised benefits of BIM and algorithm assisted design communication and coordination cannot be ignored, efforts are still imperative to visualise the FFE design more interactively and intuitively (Yan *et al*., 2011; Du *et al*., 2018). The lack of three main advancements such as BIM data interaction, human-FFE interaction and human-human interaction in BIM-enabled visualisation methods underlines the need for the aforementioned interactive and intuitive system (Du *et al*., 2018). Tantawy (2015) claims that the first and foremost requirement for space planning is the ability to visualise space in three dimensions and a keen sense of composition, scale and proportion. Studies such as that by Rasmussen *et al*., (2017) highlighted the importance of experiencing the architectural space including FFE. Rasmussen *et al*., (2017) have pointed out that it is not enough to see an architectural space, rather it must be experienced. Some studies (e.g. Li *et al*., 2017) have pointed out the shortcomings of BIM when used as technology alone. Li *et al*. (2017) suggest that poor spatial cognition is a critical shortcoming posed by existing BIM tools. The cognitive latency posed by these BIM tools has a greater role and adverse impact on FFE design decisions. In the context of this study, cognitive latency includes cognitive processes such as perception, evaluating design and judgement of the design choice (Chakraborty *et al*., 2013; Fazio, 1990).

Additive technologies such as VR are capable of bridging this gap by sealing the potential data loss within BIM and improving the stakeholder's comprehension. Furthermore, the integration of this technology is aimed at boosting the dragging productivity of the FFE sector and efficient use of the information (Li *et al*., 2017). Virtual reality is the utilisation of computer technology to create a simulated environment where the user is completely immersed in the virtual world by simulating as many senses as possible (Jackson, 2015). Thus, the user becomes a part of the virtual or immersed world within its environment whilst they can manipulate or interact with the object.

VR technology is capable of providing better communication for the key players involved in the FFE planning of the facility based on the greater design visualisation, contributing to a better understanding of the project (Jiao *et al*., 2013). Cumulative evidence has proved that VR is capable of providing a stronger sense of presence (Hoffman *et al*., 2003) and can replicate similar user behaviour as in the real world (Heydarian *et al*., 2015). Through BIM, data visualisation can be supported by VR for the virtual representation of the FFE products within virtual or real spaces beyond 3D (Greenwood *et al*., 2008) that can address retrieving and presenting information and can increase the efficiency of communication and problem-solving in an interactive and collaborative platform. This could aid the development of digital and virtual prototypes of FFE products that could be used to visualise and appraise designs by stakeholders as well as allow them the opportunity to evaluate alternatives before they are produced, built or incorporated into buildings (Cotey, 2017). ImT can potentially support the evaluation of the aesthetics of FFE products as well as other functional features that may be relevant to various stakeholders including users, clients and contractors when making decisions (Johnson *et al*., 2010).

4.5. Methodology

A novel methodology for the development and application of an interactive virtual environment in FFE design communication using BIM and a game engine is proposed. Further, this work utilises a quasi-experimental research approach with a one-group pre-test-post-test design to (Figure 4.1) understand the effectiveness of VR in enhancing the communication and coordination of critical stakeholders and the resulting understanding of the stakeholder FFE product design choice for a facility when compared with conformist methods like catalogue based (2D based) methods. This research design is widely used in STEM (Allen, 2017) and behavioural research aimed to measure changes resulting from experimental treatments or interventions on a given sample (Dimitrov, 2003). However, in the context of the FFE domain, there remains a dearth of studies that rely on similar methodologies to explore the use of immersive technologies. In this approach, the subjects act as their own control where the comparisons are made before the intervention and after the intervention assuming the fact that the difference between pre-test and post-test treatment is the due effect of the intervention occurred in the middle (Dimitrov, 2003). However, as the participants were not assigned randomly, this design does not eliminate the problems of confounding variables (Allen, 2017). Thus, this research design straddles correctional studies and a true experiment in terms of internal validity (Blalock, 2018). Studies such as Allen, (2017) have pointed out potential internal validity issues such as regression to the mean. However, the design and context of this study primarily eliminate such threats. For instance, to mitigate the issue of regression to mean, multiple tests (office scenario and meeting room scenario) were adopted for pre-test, and post-test measurements (see Ambroggio *et al*., 2012). Another limitation of this design can be attributed to the lack of a control or comparison group which limits the possibility to determine the effects of the treatment. However various studies have used this research design to assess the impact of the intervention in the field of engineering (Chalhoub and Ayer, 2018). Furthermore, these studies have demonstrated the robustness of one group pre-test and post-test where multiple experiment scenarios are explored (Chalhoub and Ayer, 2018; Krass, 2016).

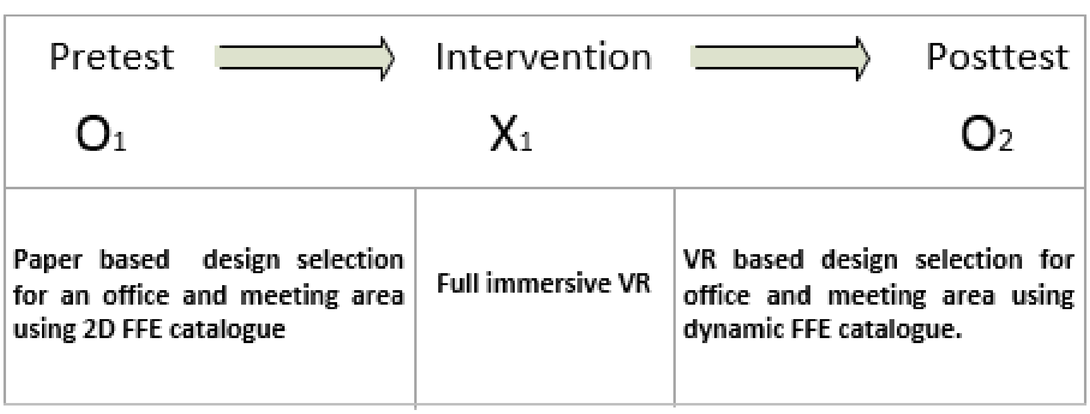


Figure 4.1: One-Group pre-test/ post-test visual representation adapted from Allen (2017)

4.5.1. Experiment Participants

Twelve participants (n=12) consisting of specialist FFE designers, architects and end-users participated in this study. The samples consisted of a diverse range of participants with ages ranging from 24 to 60. In addition to the quantitative measurements, this study provided a qualitative understanding of the proposed VR approach and user reactions which will help in future refinement of the VR simulation developed. The sample size was deemed adequate on the basis of the sample size of similar experiments where the quality of the experiment process is the focus rather than quantity and generalisability which is the case of alternative methods such as surveys (Chalhoub and Ayer, 2018). Five (5) of the participants were FFE specialists (manufacturer, designer and supplier) who had more than twenty-five years of industry experience in designing and delivering efficient spaces for various facilities. Three (3) participants were architects who had more than four years of experience in designing commercial spaces. Four (4) participants were facility end-users who use similar space in their day-to-day activities. All the participants had little or no experience in using VR or any related immersive environment enablers. The participants for this study were recruited by emails and personal solicitation. A convenience sampling technique was used to recruit participants due to the peculiarity of the study and the need for participants with specialist or domain understanding of FFE design-related tasks. Thus, convenience sampling was used to allow researchers to solicit participation from the few but most relevant subjects given this is not guaranteed in randomised sampling (Gogtay and Thatte, 2016) as well as there is a need to purposively choose participants who have the requisite knowledge relevant to the study. Table 4.1 below details the background and attributes of the sample of people who took part in this study.

4.5.2. Task

To achieve a collaborative FFE design proposal environment, participants were grouped into a minimum of two (n=2) in each group based on their availability (Table 4.1).

Table 4.1: Participant's background information

Participant ID	Age	Gender	Years of Experience	Designation	Group ID
VRFFE201901	59	M	30	FFE design specialist (Contractor)	1
VRFFE201902	57	M	27	FFE design specialist (Contractor)	3
VRFFE201903	51	M	25	FFE design specialist (Contractor)	2
VRFFE201904	53	M	28	FFE design specialist (Contractor)	5
VRFFE201905	48	M	25	FFE design specialist (Contractor)	3
VRFFE201906	36	F	6	Architect	4
VRFFE201907	28	M	4	Architect	5
VRFFE201908	35	M	11	Architect	6
VRFFE201909	24	F	3	End-user (Nurse)	4
VRFFE2019010	27	F	2	End-user (Nurse)	1
VRFFE2019011	25	M	9	End-user (Teacher)	6
VRFFE2019012	32	F	4	End-user (Teacher)	2

In the pre-test stage, each group was presented with two paper-based methods of furniture selection scenario; a) each group were asked to propose furniture for their future office space based on a paper-based 2D office space plan and an FFE catalogue (Figure 4.8) consisting of office furniture; b) the same group was asked to propose furniture for a meeting room using paper-based 2D meeting room plan and an FFE catalogue (Figure 4.8). Further, in the post-test phase, these groups were provided with the same office and meeting rooms as the pre-test, but at this stage instead of a paper-based plan and catalogue, they were immersed in the virtual office and meeting room with the aid of the interactive immersive virtual environment using a VR head-mounted display. As the entire VR system for this study was built over a distributed networked system, each participant in that group was able to see each other as avatars and was able to communicate with each other. The samples were asked to select furniture for the space provided using an interactive virtual catalogue (Figure 4.3). Please refer to section (4.6) for the details of the interactive virtual catalogue. The interactivity offered the participants the to fine-tune the geometric parameters such as colour, texture, size etc. as well as BIM meta-properties such as manufacturer, cost and product description etc. of the product that they selected. Furthermore, it allowed the users to interact with the transforms to re-position the furniture while in the VR environment. Each group member was able to interact simultaneously allowing the participants to test their design choice. A pre-test questionnaire, post-test questionnaire and open-ended interviews were employed to understand the impact. Before introducing the users to the tasks at both stages, all participants' consent was taken, and the details of the test were explained. This enabled the researcher to use the data collected such as the time taken to complete each task at each stage, pre-post task questionnaire and open interviews. Further, this study did not consider any counterbalancing measures due to the nature of the task presented. The tasks in this study were not specifically focused on any specific order of the furniture arrangements rather it was focusing on participants' FFE design choices, their resulting satisfaction and the time taken to propose those designs while in a virtual environment when compared to traditional 2D methods.

4.5.3. Pre-test and Post-test Questionnaire

A pre-test questionnaire was employed to capture; a) previous experience of the participants in using VR or any related immersive technology; b) users’ anticipation about the experience of using VR compared to the 2D method in making FFE design choice; c) perception on the shift to paperless design decision process were elicited. The post-test questionnaire focused on eliciting: a) the user experience in the virtual environment; b) perception on shifting to the paperless design decision process. These questionnaires were adapted from similar studies (e.g. Chalhoub and Ayer, 2018) which use mixed reality technology to assess its efficiency over paper-based methods in assembling electrical conduits. Furthermore, a single easy question (SEQ) method was used to elicit the participant's satisfaction level for the design choice they proposed in both pre-test and post-test, which was indicated on a Likert scale and plotted (Figure 4.10). An SEQ is the most recommended method to capture task satisfaction due to its ease and correlation to other usability metrics (Birkett, 2019). Different studies such as that by Sauro (2012) have reported that, despite SEQ's simplicity, it performs more effectively than other complicated measuring tools.

4.5.4. Proposed Framework and System Architecture

To understand the effectiveness of immersive VR in enhancing stakeholder communication and the resulting understanding of the FFE product design choice for a facility, a prototypical office space, meeting space and related FFE elements were modelled using the most popular and commonly used BIM authoring tool, Autodesk Revit (Autodesk, 2019) (Figure 4.2).

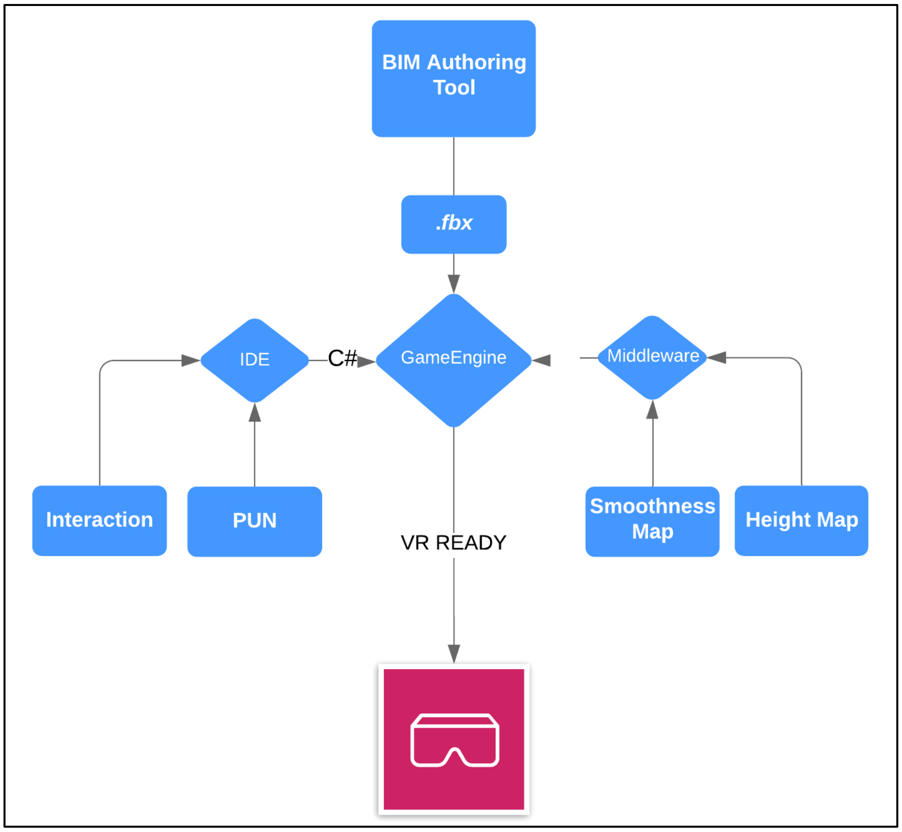


Figure 4.2: System architecture

The notion behind using Autodesk Revit as the primary modelling tool was to create parametric components that will enable the exchange of meta-data consisting of information such as manufacturer details, cost, product description, warranty, fire rating etc. This data is the information part of BIM and plays a critical role in the BIM ecosystem in analysing the FFE model. Thus, for the true functionality of the BIM as a digital workflow of information from space planning to operation of the space, it is imperative to have all the information relating to the FFE inventories that must be represented in the model and be readily available for the users in the virtual environment to interact and select FFE matching their budget and properties. Unity3D, one of the most popular cross-platform game development engines (Unity3D, 2019) was used as the platform to develop a virtual environment and related human-FFE and human-human interaction. Untiy3D was chosen over other game development engines such as Unreal due to the gentle learning curve and ease of use. Further, the scripting language used for the virtual environment development in Unity3D (C#) provides a faster application development time with high scalability when compared to other scripting languages such as C++ that are used by the Unreal engine. Unity 3D facilitated the use of a primary scripting application programming interface (API) in object-oriented programming (OOP) language, C-sharp (C#) for the development of the aforementioned interaction. In this study, human-FFE interaction refers to the added function pertaining to human-computer interaction (HCI) that allows the user to interact and manipulate the FFE in a VR environment. Similarly, human-human interaction refers to the interaction of the multi-users or virtual teams in the virtual environment between each other as well as with FFE inventories. A virtual team can be defined as "*a group of people with complementary competencies executing simultaneous, collaborative work process through electronic media without regards to geographical location"* (Chinowsky and Rojas, 2003).

A clear and modular structure for the program was achieved due to the OOP nature of the language used (Puri, 2017) which enabled reusability and faster development of the VR application for this study. Some studies (e.g., Prabhakaran *et al*., 2018) which focused on developing building mechanical services design for facilities utilised similar methodologies in developing the HCI in mixed-reality applications. As the efficacy of the VR environment critically depends on the validity and fidelity of the virtual environment (Virzi *et al*., 1996), middleware applications must be used as a tool to enhance the texture and other meta elements of the virtual environment, which will offer photorealistic computer graphics ubiquitous for both visual realism and predictability. To this end, texture-enhancing middleware was used to create diffuse, height and normal maps for all the game objects. Using such middleware applications, photorealistic computer graphics ubiquitous for both visual realism and predictability were achieved which enhances the user's "sense of presence".

Wallach *et al*. (2012) report that this sense of presence assists users in discarding disbelief and forces them to believe in the virtual world. It ought to be noted that "sense of presence" is one of the critical parameters which can increase VR efficacy (Wallach *et al*., 2012). Thus, for this study, it is inevitable to use external tools to enhance the "sense of presence". Furthermore, a low-latency multi-user platform called "Photon cloud" (PUN), which is based on a client-to-server architecture was used to facilitate the development of a scalable real-time networked VR system as well as to enable remote communication using Opus Code (Photon, 2019), facilitating a best possible audio quality. Photon cloud is also a room-based system allowing multiple users (Figs.3 and 5) to join the same room remotely from any part of the world. The rationale for exclusively implementing a low-latency system was to improve the sense of presence for the users in the virtual environment, which has a direct impact on the performance of the task presented. The utilisation of the Photon networking engine enables scaling of the virtual environment seamlessly and automatically regardless of the number of users present in the network.

For testing purposes, HTC Vive (HTC, 2019) was used as the end-user head-mounted display (HMD) device for this study. The inherent six degrees of freedom of the devices allowed the users to walk around in the virtual space and interact with the FFE inventories and their meta-data.

However, a teleporting functionality was also provided that will allow users to teleport with the aid of the handheld controller. This feature was incorporated to assist the user group who were not comfortable walking physically in the virtual world. The notion behind using a tethered HMD such as HTC Vive rather than a standalone HMD was not to compromise the realism that jeopardises the sense of presence that has a direct impact on the task. Thus, using HTC Vive as the HMD, the highly realistic graphics rendering was performed by a high-end central processing unit, which is a Windows 10 workstation with an NVIDIA GTX 1070 graphics card, which was not possible when used with a standalone HMD. Thus, a frame rate of 100 fps for all conditions was achieved in the virtual environment, which gave a high fidelity to the environment as well as eliminated the mental-physical disorientation of the users.

4.5.5. Movement in the Virtual Environment

The users in the virtual world were presented with two modes of movement: a) movement in a virtual world driven by real-world movement; b) teleportation allowing the user to transverse inside the virtual environment without moving physically in the real world. The users were given the opportunity to choose the mode of movement in the virtual space. It is worth noting that the movement in virtual space driven by real-world movement had the restriction of the user being tethered to a computer through the HMD and cables. However, teleportation could result in VR sickness in some users, as in some cases the human brain is incapable of comprehending the movement in virtual space without being moved in the physical world. However, movement in the virtual environment driven by real-world movement is more capable of presenting a higher realism and a resulting sense of presence. Virtual mesh boundaries were drawn to notify users about any approaching static obstacles such as walls. Participants tried both methods before the test and opted for the one most comfortable and suited to them.

4.5.6. The Interactive User Interface in the Virtual Environment

Creating a suitable interface that completely immerses the user in the virtual world is a bigger challenge that developers are facing (Winestock, 2018). Diegetic interfaces in VR applications are sometimes hard to achieve and can often result in many issues, such as the user losing track of the interface transform. A diegetic interface is one that exists in the virtual world but is not obviously in the direct view of the user. On the other hand, non-diegetic interfaces are those that cover the entire view angle and are easy to achieve. However, those interfaces could block the view of the user and destroy the immersion experience easily. Thus, for this study, an innovative method was adopted by replicating a digital display with an interactive interface, a handheld tablet display which is novel in the FFE literature. This enabled the implementation of a diegetic type of interface without compromising the user experience (Figure 4.3). The tablet model was anchored to the left-hand controller replicating the real-life usage and the right controller with ray cast aided functionalities such as scrolling, selecting options, drag and dropping of FFE inventories etc. Furthermore, participants reported that using such a kind of interface had a huge positive impact on the realism and the sense of presence.

4.6. Analysis

Two types of data were collected from this study; a) perception; b) performance. Perception of the user was collected from the pre-post activity questionnaire, and performance was recorded using the time duration taken to complete each task. Details of perception and performance eliciting are reported in the next section. Data from these were further subjected to statistical analysis to understand their significant difference from pre-post treatments. In addition, open-ended questionnaires were used to understand full and meaningful answers with respect to participants' knowledge as well as feelings after the VR treatment. These findings are presented in the next section.

4.7. Result

4.7.1. Performance

All the participants were able to perform the task successfully using the 2D plan and FFE catalogue as well as in the virtual environment presented to them. Time taken (Figure 4.6) by each group during pre-test and post-test were recorded to understand the perception of the user when introduced to an immersive digital environment. In the pre-test, time was recorded from the moment the participants were given the 2D plan and FFE catalogue (Figure 4.7), whereas in the post-test the time was recorded from the moment that the participants joined the distributed room and users were able to see and communicate to each other's avatar. In both stages, the time recording ended when the users declared that they are satisfied with the design choice they proposed. In the VR environment option was provided to save each group's choice, which was later converted into 2D plans (Figure 4.8). On average, each group spent 9 minutes and 8 minutes respectively to complete the paper-based office and meeting room task and 6.3 minutes and 5 minutes, respectively, to complete the office and meeting room tasks in a virtual environment. An independent sample t-test (Table 4.2) was performed to identify the statistical significance in the duration taken by both the control and experiment groups to perform each scenario presented to them.

There was a significant difference in the score for pre-test (office space task- M=542.5,SD=90.13) and post-test (office space task- M=390.5,SD=47.12) conditions; t(10)=3.66, p =0.004 and pre-test (meeting space task- M = 480, SD=73.61) and post-test (meeting space task M=303, SD=26) conditions; t(10)=5.526, p=0.001.The design choice of both pre-test and post-test were recorded (Figure 4.8) to examine any difference in design decision after the treatment.

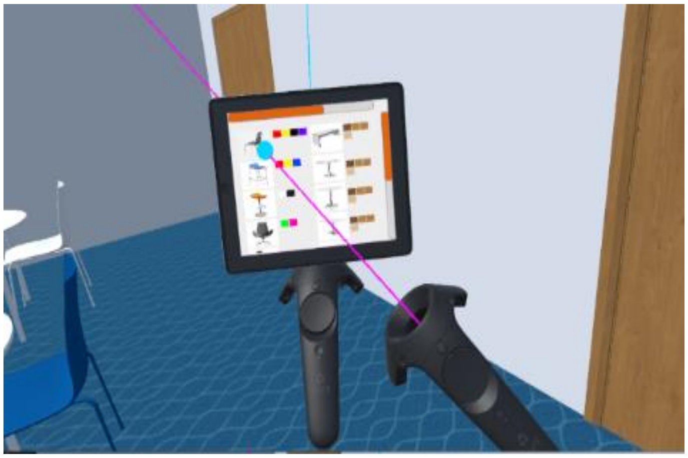


Figure 4.3: Dynamic and Interactive virtual catalogue

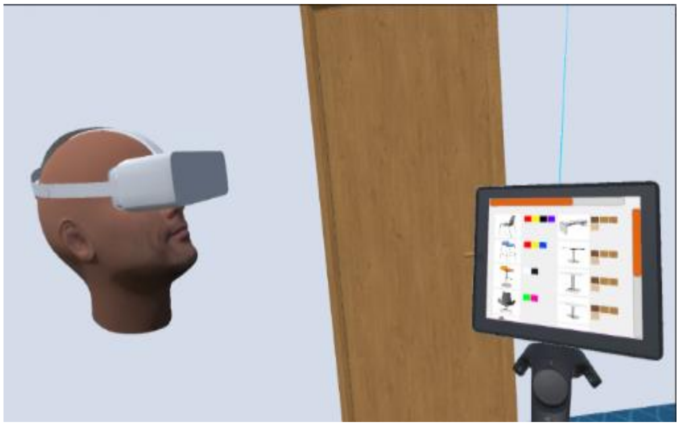


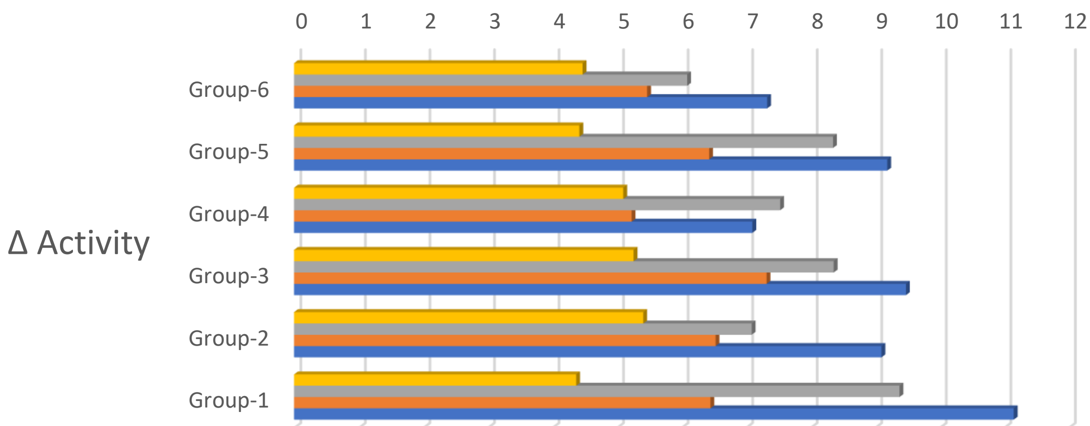
Figure 4.4: Users testing design choices in the virtual environment

Figure 4.5: Users interacting with FFE elements

It ought to be noted that this study did not focus on the principles of space planning, design standards or design rationale such as the work triangle followed by designers (Jones and Kapple, 1975) to assess the quality of design choices made by the participants. Rather, this study tries to understand the effectiveness of design decisions whilst using VR compared to traditional FFE design selection methods and the resulting satisfaction level of the participants with respect to the design that they proposed.

Table 4.2: Independent sample t-test for significance in time between treatments

	n=12	Levene's Test for Equality of Variances: F	Sig.	t-test for Equality of Means: t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference: Lower	Upper
Office Space	Equal variances assumed	1.69	0.222	3.66	10	0.004	152.0	41.52	59.48	244.51
	Equal variances not assumed			3.66	7.54	0.007	152.0	41.52	55.22	248.77
Meeting Space	Equal variances assumed	4.15	0.069	5.52	10	0.000	176.16	31.87	105.13	247.19
	Equal variances not assumed			5.52	6.23	0.001	176.16	31.87	98.86	253.47



	Group-1	Group-2	Group-3	Group-4	Group-5	Group-6
Δ Meeting Space(posttest)	4.37	5.41	5.26	5.1	4.42	4.47
Δ Meeting Space(pretest)	9.38	7.09	8.36	7.53	8.35	6.09
ΔOffice Space(Posttest)	6.45	6.53	7.32	5.23	6.43	5.47
Δ Office Space(Pretest)	11.15	9.1	9.48	7.1	9.19	7.33

Figure 4.6: Time taken to complete each activity

4.7.2. Perception

An in-depth literature review revealed that VR technologies are disrupting the construction industry, creating a major shift in design communication. Therefore, it is inevitable to explore the perceptions of the participants. Thus, a pre-post-sessional questionnaire and open-ended questionnaire were employed to understand this perception. The pre-session questionnaire revealed that none of the users (n=12) had any experience in using similar technology enablers. Furthermore, all the participants (n=12) felt that VR would be easy to use. Two of the participants reported concerns about the quality and degree of realism that can be achieved compared to real-life settings. More than half (n=7) of the users stated that they would want to use a paper-based selection process for information delivery. Five participants believed that VR technology could potentially change the way information is delivered, even though they did not have any previous hands-on experience in using such technologies. Further, pre-treatment design proposal satisfaction for the paper-based design was recorded (Figure 4.9). Then, participants were exposed to VR treatment.

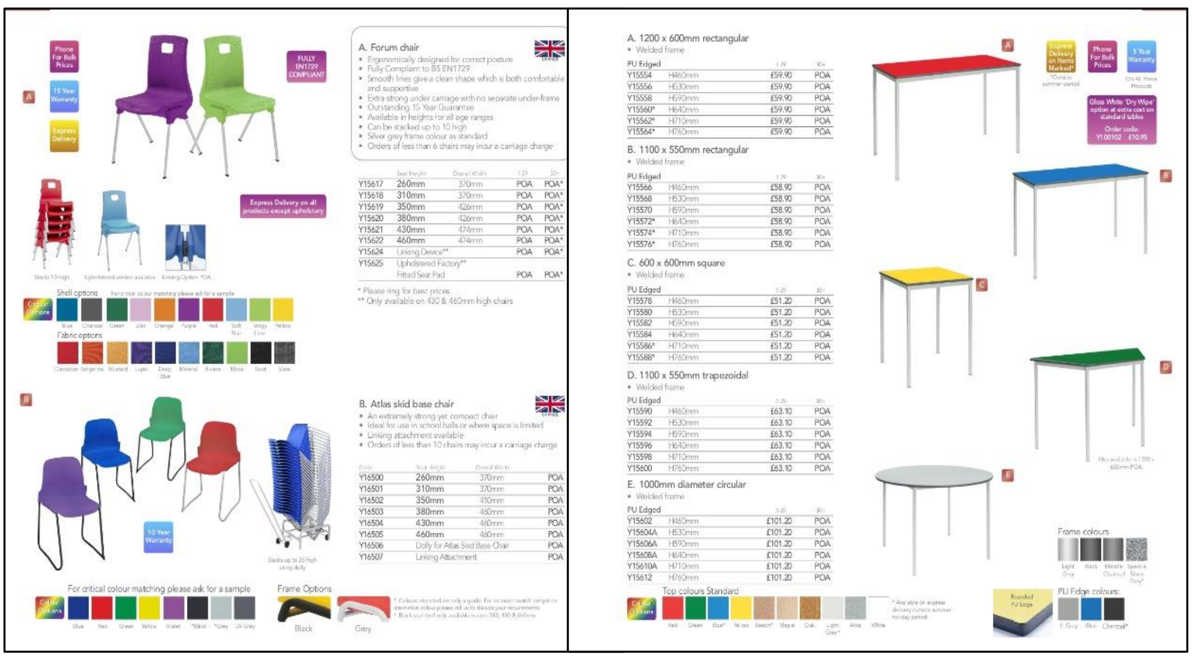


Figure 4.7: 2D FFE Catalogue (Springfield, 2019)

After completing the design proposing task in the virtual environment, participants completed the post-sessional questionnaire. All the participants (n=12) indicated that they consider VR to be a highly effective medium for design information delivery. Also, it ought to be noted that all of the groups proposed a different layout or tested a different design in a VR environment (Figure 4.8) compared to their paper-based proposal. Most of the participants indicated that design selection using VR encouraged them to test various layouts and different combinations of FFE. Most of the participants preferred a lighter FFE colour when compared to the paper-based method.

One of the users indicated that “I would definitely like to have a brighter room and this virtual experience made me change the colour choice I made in the earlier selection (paper-based). With VR I can visualise the furniture colour with respect to the room colour. This itself is enough to advocate the shift from paper-based to a virtual environment”. Another user indicated that “while trying the paper-based I was not sure if the office and meeting area will be spacious enough for user movement, even though all the dimensions were marked on the drawings as well as on the FFE catalogue provided. However, while in the second try (VR based) I was able to confidently populate the room with different FFE layouts and with greater satisfaction that space is used in its most efficient way”. An FFE supplier commented, “We are very satisfied with the output VR could bring into our business and we will take all necessary steps to set up a virtual space at our facility. Also, we will train our “staff to develop such content for our client”. Another user reported, “The visual stimuli provided by the digital projection facilitated the process to select the suitable furniture for space. The drawing given did not provide enough input to imagine the space or the furniture fittings which suit the space. Based on this demonstration, I would prefer to have VR as a mode of presentation by the FFE contractors for our future projects.”

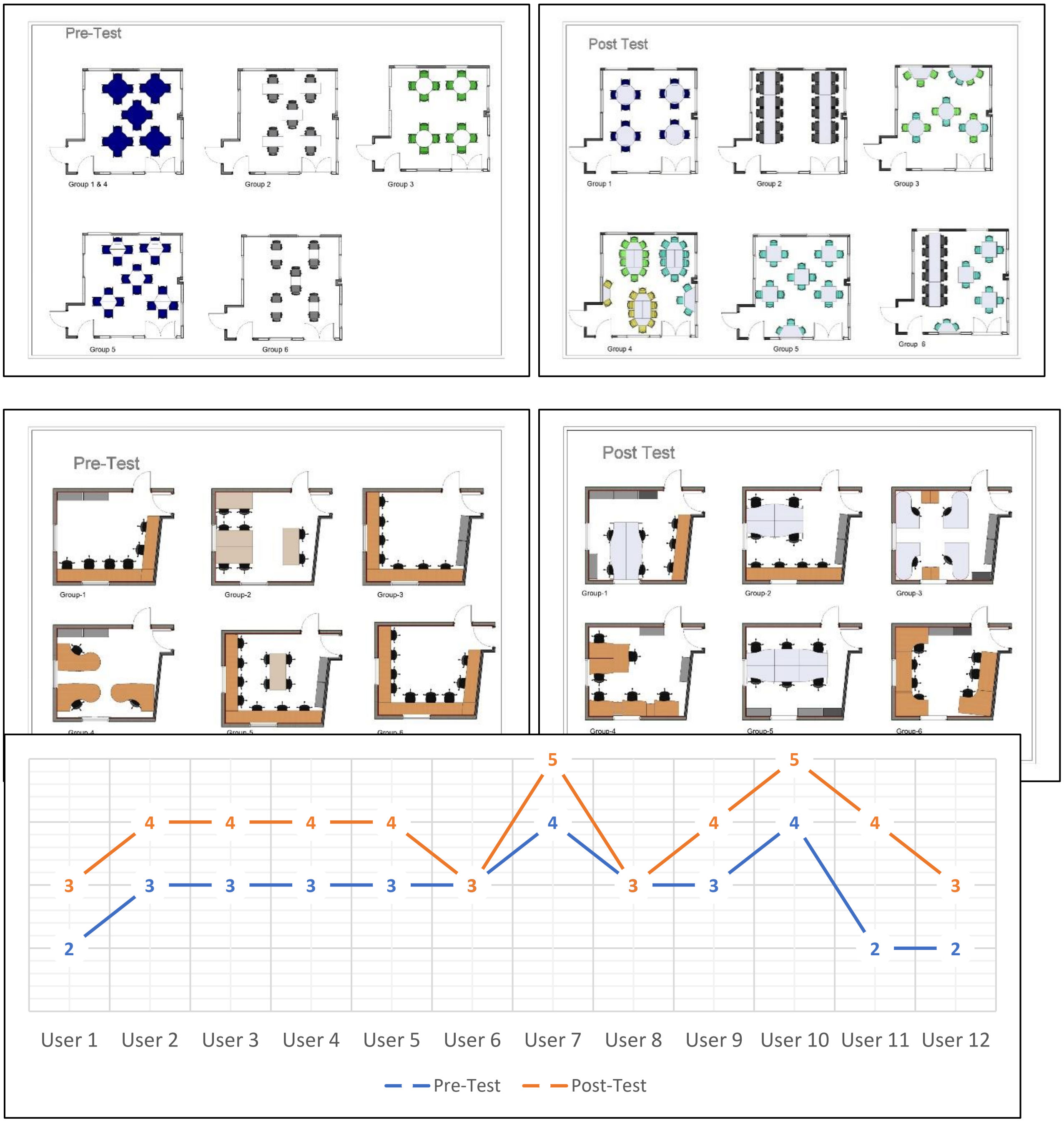

Pre-Test
Post Test
Pre-Test
Post Test
User 1
User 2
User 3
User 4
User 5
User 6
User 7
User 8
User 9
User 10
User 11
User 12
Pre-Test
Post-Test

Figure 4.9: User satisfaction level

Most of the users indicated that VR enabled them to look into the minute details of the FFE such as edge, colour etc. which were impossible in the paper-based task. Some users (n=2) reported virtual reality sickness. It must be noted that care was taken to maintain a frame rate level of 100 frames per second to eliminate any VR sickness and improve the quality and degree of realism to enhance the resulting sense of presence. Further interviews with the users (n=2) who reported VR sickness revealed that a certain physical condition is responsible for the effect, and it is not the virtual environment which has any direct relationship with the experience. A majority of the users identified that the virtual environment provided extreme flexibility in choosing furniture based on their texture, colour and aesthetics as well as based on the interior space and colour of the rooms which was impossible when done through conformist methods. All the users unanimously agreed that they would prefer to shift to a VR-based decision process for future engagements.

Furthermore, users reported that the virtual presence of the other participants in the group encouraged the effective testing of different choices, the sharing of their design choice and the visualisation of each design choice simultaneously. One of the FFE contractors reported that "the possibilities of remote communication and visualisation opens up the window for us to collaborate with our FFE designer/manufacturer who is located hundreds of miles away from us. Usually, we have to send one of our team members to their facility to discuss the design which is financially as well as environmentally unfriendly. We wish to develop this tool further and include it in our supply chain workflow". The post-session questionnaire also revealed that all the participants had a higher level of satisfaction (Figure 4.9) with the design that they proposed compared to the paper-based proposal. However, few participants (n=2, users 6 and 7) reported the same level of satisfaction compared to the pre-test. It is worth noting that these participants earlier reported VR sickness whilst performing the task.

Table 4.3: Independent sample t-test for significance in satisfaction

		Levene's Test for Equality of Variances		**t-test for Equality of Means**						
n=12		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Pre-Post Satisfaction	Equal variances assumed	0.216	0.646	-4.84	22	0.001	-1.16667	0.2410	-1.6664	-0.66686
	Equal variances not assumed			-4.84	21.95	0.001	-1.16667	0.2410	-1.66652	-0.66681

This could have potentially influenced their user experience, which made them report the same level of satisfaction compared to the pre-test. Some of the users also (n=3) reported that the chosen HMD felt bulky for long-term usage. An independent sample t-test (Table 4.3) was performed to identify the statistical significance of the difference in pre-post-treatment satisfaction levels. There was a significant difference in the score for pre-treatment M=2.833, SD=0.577 and post-treatment M=4, SD=0.603 conditions; t (22) = -4.841, p = 0.001.

4.8. Discussion

In this study, a one-group pre-test-post-test design is adopted due to its suitability in understanding the behavioural factors in determining the effect of the treatment on a given sample (Dimitrov, 2003). This research design's usability is well known within the STEM disciplines due to its simplicity in implementation and is suitable when one group of participants are available to study (Campbell, 1957). However, this research design has some threats to internal validity such as regression to the mean (Campbell, 1957). Considering the proof-of-concept nature of this study, this threat to internal validity needs to be considered as a limitation of this study.

The study revealed interesting insights into the effectiveness of a VR-based interactive FFE virtual environment in FFE's design communication and coordination when compared to the traditional methods (2D-based methods) practised across this industry. Time taken to complete the presented task (Table 4.2) suggests that FFE design choices made using the virtual environment require significantly lesser time compared to the 2D-based methods. This also suggests that if there is no sacrifice in the quality of the design choice, there is a direct benefit in using VR as a tool for enabling effective design communication among the critical stakeholders. Furthermore, this result complements the findings of Wang and Dunston (2007) which suggest that usage of VR HMD shortens the completion time and less workload for a task which demands spatial orientation requiring local situation awareness. However, it must be noted that task completion time in a virtual environment can be impacted by various levels of fidelity characterisations such as representational, interaction, information and perception of the environment as observed by Cooper *et al*., (2018) and various other studies. This does not imply higher the fidelity, the higher the task performance in the virtual environment. For instance, a study by (McMahan *et al*., 2016) to assess the task completion efficiency using various levels of interaction fidelity found that semi-natural interaction fidelity may have an adverse effect on the task presented than low and high-level interactions, representing “uncanny valley” phenomenon (Mori,1970). Similarly, various studies (e.g. Hamstra *et al*., 2014) have tested empirically the quantifiable benefits of a higher degree of fidelity. Surprisingly these studies have concluded that enhancement of each characterisation based on the task at hand has beneficial impacts on the task performance and resulting completion time (Dahlstrom *et al*., 2009). Further, this study didn’t consider the impact of using sensory modalities like haptics, which might have a positive impact on the task at hand. However, this must be tested and proven in future studies. The authors were expecting to find a similar or possibly better performance in completing the paper base task because of participants' familiarity with the mode of visualisation. However, it is noteworthy to observe that the VR-based task significantly outperformed the paper-based task, even though the participants had no or very little experience with VR.

The experiment also revealed that all the design decisions made using the paper-based method changed when the participants performed the same task in the virtual environment (Figure 4.8). This is because spatial perception plays a key role in the context of understanding an architectural space and using that space effectively. Spatial perception is a complex internal information processing task (Marr,1982) and its goal is to estimate, identify, recognize and give meaning to objects and spaces with which the human interacts (Palmer, 2003) which in the context of this study is human-FFE interaction. Studies (e.g. Paes, 2017) have pointed out that better spatial perception leads to an enhanced interpretation of spatial elements, which leads to the conclusion that within the immersive virtual environment, displayed spatial geometric information of the FFE elements facilitates better understanding and is processed better by the user. However, in the case of paper-based methods, the chances of acquiring such spatial perception are nearly impossible.

This finding is noteworthy, as many of the participants in this study had more than 25 years of experience in FFE product design, manufacture and space planning using traditional methods, yet they preferred a different design choice in the virtual environment.

Further, this study also revealed a higher level of user satisfaction in a virtual environment when compared to the 2D-based method. Papagiannidis *et al*., (2013) pointed out that satisfaction is a key ingredient in building consumer loyalty and end-user satisfaction is a major goal in every user-system interaction. It ought to be noted that, this user satisfaction is the ultimate element that triggers the user's purchase intention of a product or design and this has been proven empirically by various studies (e.g., Papagiannidis *et al*., 2013). The findings from this study could be applied not only in design decisions using virtual reality but also in multi-dimension aspects such as v-commerce or virtual FFE showrooms which allows users to immerse themselves remotely and confidently purchase FFE elements based on the design choice they made in the virtual environment.

This study also probed into the challenges including the infrastructural issues posed by the technology providers. One such infrastructural issue is the physical weight of the HMD which can hinder the user experience due to physical discomforts. However, the chosen HMD for this study was the basic version of HTC Vive which has been superseded recently by a lighter version, thanks to the rapid improvement in ICT during the last few years. Furthermore, FFE contractors raised the concern of interoperability issues that exist between the current BIM authoring tools and immersion and interaction content developing tools. This is one of the major concerns that need to be addressed if the full potential of VR needs to be utilised. Reports have highlighted some limitations with current applications as merely an over-glorified extension of traditional 2D communications, neglecting other practical and human sensory needs which will normally be engaged when examining physical objects (Whyte, 2001; Johnson *et al*., 2010). It ought to be noted that existing VR applications are merely acting as a vehicle to maintain traditional visualisation practices, ignoring the above mentioned critical factors along with human factors, behaviours and other perceptual and practical needs (Johnson *et al*., 2010).

4.9. Design, Architectural and Procurement Implications

VR can be considered one of the most promising technologies in the construction sector and will revolutionise this sector in the next years (Gov.UK, 2018). This study differs from previous literature which focused on VR's application in the FFE sector under a multi-perspective; a) this study utilises a fully immersive virtual environment which provides spatial cognition to its users like a physical environment; b) this study utilised a distributed VR system that replicated the real-life collaborative environment were human-human interaction is critical; c) this study purposes a novel methodology for development and application of an interactive virtual environment and the utilisation of a hybrid user interface that alleviates the limitations of a diegetic and non-diegetic interface. It should be acknowledged that this study used a smaller sample size to test the effectiveness of the system on FFE's workflow. Thus, the findings should not be generalized on an industry-wide level, the findings of this study do support the claim that when implemented properly, VR can enable FFE wide productivity benefits over paper-based methods. Further, the system framework and the findings in this study can be applied not only for the FFE design decision-making in the construction sector but also in the virtual commerce aspect of the FFE industry. This will aid the FFE suppliers to switch from physical stores to virtual stores, providing an opportunity to display a vast variety of virtual products without investment in the warehouse space and products focusing more on experience-based marketing. Further, the relevance of such a system for the consumers cannot be overemphasised considering the dynamic purchase behaviour of the consumers as well as the unwillingness of the clients to explore vast shop floor areas to explore the variants of FFE products that are put on display (Meadows, 2020). However, it is important to note that one of the key factors contributing to user satisfaction and task productivity in a virtual environment is the richness of the user experience in the virtual environment. Thus, the industry must have to put careful attention during the development of the virtual environment to eliminate the factors that contribute to effects like simulator sickness which will demotivate the user acceptance of VR technology.

4.10. Limitations

The work presented here is a proof of concept employing an experimental design which validates the technological use and exploration of its efficiency compared to the current paper-based and 2D interface-based workflows. The limitations of this study can be related to the test environment, research design and non-consideration of space planning concepts. This experiment did not take place in an actual FFE project set-up, rather it was performed in a controlled environment. Also, at the time of this study, major interoperability issues existed between BIM authoring tools and immersive content creator tools. The content for this study was created using various middleware tools and several iterations before being interactive VR ready. While FFE sectors' BIM adoption is gaining momentum, the implementation of VR into their workflow without addressing the interoperability issues could adversely affect the workflow. Also, additional training might be required for the FFE content developers to create an interactive VR experience which is omitted from the analysis of this study. Therefore, additional investments might be required including training needs over the current workflow for organisational-wide adoption of this system. Moreover, the entire system was built to achieve a high-fidelity ecosystem which requires high-end processors and dedicated space which could add on to the investments. Further, even though the single group pre-test-post-test design is widely used in studies of this nature, this research design does not account for many confounding variables that may pose threat to the internal validity of the study. Thus, for studies that need to be done on a larger scale, careful consideration of a more robust quasi-experimental design must be done. Lastly, this study did not consider any principles or guidelines of space planning to assess the quality of design choices made by the participants; rather, the study tries to understand the variations in design decisions while using the virtual environment and the effectiveness of networked user environment compared to traditional FFE design selection methods and the resulting satisfaction of the user with respect to the design that they proposed.

4.11. Conclusion

The authors propose a novel methodology for the application of interactive networked VR in the FFE design selection process as well as investigate the impact of introducing VR into the BIM workflow. This study is the response to the need for a platform that streamlines the design review process in the FFE sector through the engagement of all critical stakeholders assisting them with spatial comprehension, which is a critical factor for any FFE selection and design review process. Thus, this study extends the synergy between the technology integrating immersive environment which aids in tackling the challenges which exist in perception imposed by conventional 2D methods of design selection and review.

A prototypical interactive networked VR system was presented and discussed. An experimental setup consisting of FFE experts with more than 25 years of experience, architects and end-users were used as the samples. Findings report that the presented framework can highly improve the efficiency, design coordination and productivity as well as highlight a few of the infrastructural issues for scaled-up deployment of this system. Furthermore, this study also investigated the perception of the users before and after the test. Also, the duration for both paper-based and VR based tasks was measured and found that VR tasks required significantly lesser time compared to the traditional method, and a statistically significant difference in the overall time was identified. Furthermore, all the participants proposed a different layout or tested a different design in the VR environment compared to their paper-based proposal. Most of the participants indicated that design selection using VR encouraged them to test various layouts and different combinations of FFE. The majority of the users identified that the virtual environment provided extreme flexibility in choosing furniture based on their texture, colour and aesthetics as well as being based on the interior space and colour of the rooms, which was impossible when done through conformist methods. Further users reported that the virtual presence of the other participants from the sub-group encouraged the effective testing of different choices and sharing their design ideas and visualising them simultaneously encouraging a collaborative culture in the industry. The satisfaction level of the participants during pre-post treatments was measured and a significant improvement in their satisfaction post-treatment was observed. However, some of the users reported infrastructural issues, such as the weight of the HMD, as a concern that may restrict some users from using this system in the long run. This study contributes to the body of knowledge by the empirical demonstration of the potential of interactive distributed VR for the FFE design selection process compared to the present paper-based approach, with the aid of industry-developed BIM and industry experts.

Chapter 5: BIM-based Immersive Collaborative Environment for Furniture, Fixture and Equipment Design

Abhinesh Prabhakaran[1], Abdul-Majeed Mahamadu[12], Lamine Mahdjoubi[1] and Pawel Boguslawski[3]

[1]Department of Architecture and the Built Environment, University of the West of England, Bristol, UK.

[2]Department of Construction Management and Quantity Surveying, University of Johannesburg, Johannesburg, South Africa

[3]Institute of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland

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Abhinesh Prabhakaran [a], Abdul-Majeed Mahamadu [b, c], Lamine Mahdjoubi [a], Pawel Boguslawski [d]

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Statement of Contribution: This journal article is an empirical study which proposes a novel methodology for the development and testing of a distributed VR application for the FFE sector. My contribution as the main author of this paper was to conceive the presented idea, development of the methodology and questionnaires, development and testing of the distributed VR application, analysis and discussion of the results, drafting of the paper and revise the paper based on the journal reviewers' comments. Co-authors of this paper are my PhD research supervisors and advisor who provided the mentorship, guidance, review of research concepts, methods and review of manuscripts. My overall contribution to this paper is estimated between 80-90%.

Abstract

One of the most critical issues related to the current application of virtual reality during design appraisal is the inability to have a collaborative virtual environment where a group of geographically remote stakeholders can interact and communicate effectively in real-time. This paper addresses this shortcoming by proposing a collaborative furniture, fixture and equipment virtual environment (COFFEE) that allows concurrent multi-users to interact, communicate and collaborate virtually during the design appraisal of interior furnishings of a facility. The testing of the proposed system among various construction stakeholders (n = 26) to demonstrate the usability and functionality showed a high degree of acceptance by stakeholders as a result of improved visualisation, multi-user communication, and collaboration in the virtual environment. In practice, COFFEE is expected to assist interior design stakeholders to make informed decisions and create shared understanding before the commencement of construction activity.

Keywords: Multi-user, Virtual reality, Design communication, Immersive collaboration

5.1. Introduction

In recent years, various segments of the Architecture Engineering and Construction (AEC) industry, including the Furniture Fixture and Equipment (FFE) sector, which is one of the critical segments of interior design have witnessed a steady increase of interest in the use of immersive technologies such as Virtual Reality (VR) aimed at improving the work process. The potential of VR in the AEC industry has been explored in the past by various studies and in particular studies (e.g., Zhang *et al*., 2019; Kaleja and Kozlovska, 2017) have demonstrated the effectiveness of VR during the appraisal of a building's interior design. While many of these studies so far have been focused on understanding the potential of VR during the appraisal of the interior design of a building, various technical limitations exist in the current state of VR that could restrain the full-scale application and adoption of this technology. One of the most critical issues is related to the inability to have a collaborative virtual environment where a group of geographically remote stakeholders can interact, effectively communicate, and appraise designs collaboratively in real-time (Roupé *et al*., 2020). This limitation has not been addressed because the development process for such distributed VR applications is complex and the infrastructure requirements for such developments are resource-demanding (Podkosova *et al*., 2016). This has been addressed in this study by proposing a more streamlined approach through the development and testing of a novel collaborative VR tool for the FFE sector named COFFEE. Even though the concept of COFFEE could be applied to wider segments of interior design, the FFE sector which is one of the critical segments of the interior design was chosen for this study to demonstrate the usefulness of COFFEE. The rationale behind choosing the FFE sector for testing the usefulness of COFFEE was because FFE plays a critical role in connecting the built environment with its occupants who spend 90% of their time indoors (Ergan *et al*., 2019). The amount of time that occupants spend indoors emphasises the significance of FFE and its effective arrangements in influencing human experience within a built space, which demands a collective decision-making environment. The findings of a study by Saffo *et al*. (2021) suggested that tasks performed in a collaborative virtual environment can yield very high efficiency when compared with single-user virtual environments.

Therefore, in this study it has been proposed that the aforementioned shortcoming of the current state of the VR environment could be addressed, to enable concurrent multi-users to interact, communicate and collaborate virtually and asynchronously during design decision making in the FFE sector. COFFEE utilises building information modelling (BIM) and a game engine that is integrated with a real-time, cloud-based, client-server architecture for scalable, low latency, cross-platform and stable multi-user interaction. A series of tests were carried out among FFE stakeholders to assess the usefulness and effectiveness of COFFEE during design appraisal.

The remainder of this paper has been structured into seven sections. In Section (2) the current state of the application of VR in communicating design in the FFE sector has been explored. Section (3) provides an overview of the application of distributed VR in the AEC sector and Section (4) contains a detailed explanation of the methodology adopted for this study. Further, Section (5) details the system framework, development method followed and integration of COFFEE with Scrum for lean construction and Section (6) provides the details of the testing and evaluation of COFFEE. In Section (7) the features and capabilities of COFFEE have been compared with other off-shelf VR applications. Finally, Section (8) provides the conclusion and implications of this study.

5.2. Immersive Technology and Design Communication in the FFE Sector

The process of design communication in the FFE typically involves a linear flow of information among the stakeholders starting from the designer to the end-user/client. Shannon, (1948) explained this mode of communication as the theory of linear standard communication process involving encoding and decoding of messages at transmitting and receiving ends, which often lead to potential noise in the communication transmitted. In FFE's context, the designers create a design, which is then encoded into a set of plans which are then communicated among the stakeholders. Until recently, FFE's communication of design relied on traditional tools and methods such as 2D technical drawings, sketches, and pictures resulting in poor stakeholder engagement and a decline in productivity (Prabhakaran *et al*., 2021) as a result of the noise created at the decoding stage. The poor stakeholder engagement and decline in productivity could be attributed to the fact that not all stakeholders involved in the FFE's design appraisals have similar comprehension capabilities. This difference among the stakeholders has been widely acknowledged since the seminal work by Schön, (1988), who points out that the end-user/client and designers occupy an entirely different design world making design communication more challenging. However, recently FFE sector has embraced digital processes, such as Building Information Modelling (BIM) to create data-rich three-dimensional (3D) models to communicate its designs with stakeholders (Cotey, 2017). Although the adoption of BIM has assisted the FFE sector to communicate its design with its stakeholders effectively, the sophistication of the current designs has reached a point where it exceeds the comprehension and interpretation capabilities of some of the critical stakeholders, limiting them from engaging effectively in the design appraisal process (Walasek and Barszcz, 2017) because of the so-called "black box effect" that refers to a system that lacks transparency and legibility in communicating with the participants (Rahimian *et* *al*., 2019).

In recent years, human-computer interfaces, such as VR, have been introduced in an attempt to address the communication and engagement gap in the FFE sector, with aim of offering a reliable extension of BIM for more advanced visualisation as well as communication (Rasmussen *et al*., 2017). Time-saving and the reduction of costly physical prototypes are some of the well-known benefits derived from the application of VR (Wolfartsberger, 2019). The opportunity for immersive visualisation offered by VR has a critical role in the FFE sector, as FFE's procurement is often based on three primary criteria- aesthetics, cost and functionality, of which aesthetic merit is the most valued during a design appraisal (Yoon *et al*., 2010). Yoon *et al*. (2010) noted that, when the cost and functionality of the FFE alternatives are similar, people tend to choose the option that is more aesthetically appealing. Thus, the traditional means of product presentation offered by the FFE sector using either a two-dimensional (2D) plan or 3D models on a 2D interface are not sufficiently effective for the stakeholders to gauge the aesthetic merits during the design communication. However, the use of VR has offered a step-change in the way the FFE designs are presented to the stakeholders. In a study by Sampaio *et al*. (2010), it was concluded that, compared with the indirect experience offered by 2D presentation mediums like catalogues and sketches, the immersive virtual experience offers better stakeholder perception which is close to direct experience with space. In some studies (Oliver, 2019; Roupé *et al*., 2020) it has been noted that immersive visualisation can increase the stakeholder's information bandwidth thus reducing the time required for effective communication. Oliver, (2019) concludes that virtual spatial proximity offered by immersive VR reduces the perceived spatial and temporal distances, thus enriching the perception of richness in effective communication. While much of the studies in the past have focused on developing isolated VR experiences, studies (e.g., Liu, and Kaplan, 2018; Oliver, 2019) highlight the importance of co-presence in VR which is considered the antecedent of effective communication among the stakeholders. A study by Schnabel and Kvan, (2002) reiterated the importance of co-presence in VR and concludes that design communication in a collaborative, immersive, virtual environment can yield new and meaningful results. In VR assisted design communication, co-presence could only be possible through the development of a collaborative VR system that allows concurrent multi-users to interact, communicate and collaborate during the design-making process.

5.3. Distributed VR

Nayak and Taylor (2009) described a project team as a virtual team, which Chinowsky and Rojas (2003) defined in the context of the construction industry as “a group of people with complementary competencies executing simultaneous, collaborative work processes through electronic media without regard to geographic location”. Apart from the benefits offered by these virtual teams, the construction literature has noted potential challenges that are faced in virtual project teams such as issues relating to communication, development of trust, and quality control (Nayak and Taylor 2009). Furthermore, unlike other sectors of the AEC, FFE’s design communication involves stakeholders with both technical and non-technical backgrounds which makes the communication process even more difficult. Distributed VR can provide a possible solution to these challenges in the FFE’s communication process. Roehl (1995) defines a distributed VR (DVR) as a simulated world that runs on multiple processors that are connected by the internet and the users in the virtual environment can interact remotely and simultaneously in a meaningful way in real-time, sharing the same virtual world. Even though the concept of DVR can be traced back to the early 1990s, recent improvements in hardware, software and high-speed internet connectivity have rendered its application viable and worthwhile (Miltiadis, 2016). The central concept of DVR is a multi-user virtual environment, where participants can meet, collaborate and interact regardless of their geographic location, which has become one of the most promising uses of VR. Since its first ideation two decades ago, DVR has been lauded as an effective platform that has aided the communication of ideas effectively within a team. Since then, DVR technology has been explored by researchers from various domains.

5.3.1. Related Works

Even though the potential of VR for design communication in the FFE sector has been established in a plethora of studies, there exists a dearth of studies that utilises the application of DVR in the AEC industry generally (Tea *et al*., 2022; Podkosova *et al*., 2016) and FFE sector specifically (Prabhakaran *et al*., 2021). Some of the most notable applications of DVR for collaborative communication in the AEC industry have been observed in studies by Boton (2018); Tea *et al*. (2021); Roupé *et al*. (2020); Du *et al*. (2018) and Prabhakaran *et al*. (2021). Du *et al*. (2018) and Boton *et al*. (2018) proposed a BIM-based multi-user system for collaborative communication in an immersive virtual environment. In their study, Du *et al*. (2018) and Boton (2018) demonstrated that DVR could improve interpersonal interactions and enhance communications in a construction project through co-presence. Similarly, Roupé *et al*. (2020) proposed a collaborative design system for creative and shared design also reiterating the findings of Du *et al*. (2018) and concluding that multi-user immersive VR applications can enhance the stakeholders' understanding of the design and improves their communication and collaboration within the team. The effectiveness of DVR in the FFE sector was proposed by Prabhakaran *et al*. (2021), who compared 2D-based design and immersive DVR. Their study also concluded that the sense of being in the virtual environment has a significant effect on the users' performance in completing tasks whilst in the virtual environment. Cumulative evidence from these studies suggests that the use of DVR for the collaborative decision-making process can enhance cognition among remote users, aids in better understanding of designs enable effective participation of all stakeholders and encourages knowledge sharing. However, based on an extensive review of the literature, it is evident that gaps in knowledge remain. Firstly, there are very few studies (Du *et al*. 2018; Boton, 2018) which integrate BIM and DVR for design communication and collaboration. The synergy between BIM and DVR is critical for sectors, such as the FFE, which are currently on the path of adopting BIM and other digital technology. Secondly, in existing studies in which the integration of BIM and DVR was demonstrated, it was noted that the development of BIM-based DVR applications is challenging, cumbersome and time-consuming as they require multiple iterations and lacks a synchronised flow of information between the distributed VR and the BIM environment. Furthermore, existing studies lack rigour in the development and testing of the DVR applications, which will limit their deployment in practice. Also, existing studies were not focused on developing a high-fidelity DVR environment, which is critical for a sector such as the FFE. In various studies (Ragan *et al*., 2015; Slater *et al*., 2009), it has been noted that the visual fidelity of the immersive virtual environment has a positive impact on the user’s experience and can trigger more realistic responses. Thus, visual fidelity has a significant impact on the FFE stakeholder's design decision, as aesthetic merit is most valued during an FFE design appraisal (Yoon *et al*., 2010). The limited number of literature and the aforementioned gaps could be attributed to the development process for DVR applications being complex and to the infrastructure requirements for such developments that are resource-demanding (Podkosova *et al*., 2016). In a bid to address these gaps, in the present study, a streamlined approach is proposed through the development and testing of a novel collaborative

DVR tool for the FFE sector, named COFFEE.

5.4. Methodology

A novel methodology was proposed for the development and application of a distributed virtual collaborative environment for the communication of FFE design using VR. An exploratory sequential mixed method was subsequently used to validate the developed tool involving 26 FFE stakeholders (Designers, Manufacturers, Contractors, Architects and End-user/Clients). The approach began with a quantitative phase during which questionnaire surveys aided in the elicitation of data related to usability and experience of using COFFEE, followed by a qualitative phase where open-ended interviews were used to obtain FFE experts' perspectives about COFFEE. Figure 5.1 illustrates the research framework for this study. The System Usability Scale (SUS) questionnaire (Brooke, 1996) was used during the quantitative phase of this study to assess the perceived usability and validity of COFFEE.

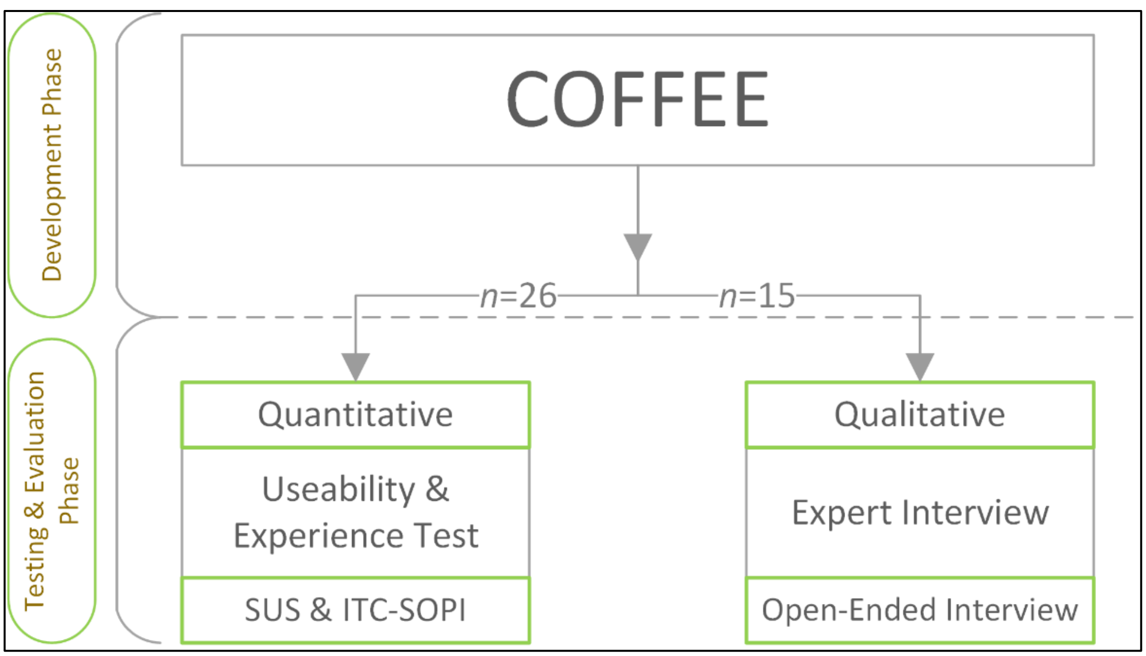


Figure 5.1: Research framework

The participants' perceived sense of presence (SoP) whilst using COFFEE was measured, as extant research (e.g., Brade *et al*., 2017; Krassmann *et al*., 2020; Lorenz *et al*., 2018; Busch *et al*., 2014) suggested that the sense of presence in the virtual environment has a stronger connection with the usability of the system and will encourage the acceptance of VR technology. Hence, measuring participants' sense of presence (SoP) while using COFFEE was relevant. The Independent Television Commission Sense of Presence Inventory (ITC-SOPI) developed by Lessiter *et al*. (2001) was used to measure participants' SoP whilst using COFFEE focusing on the four key constructs a) *sense of physical space*, b) *engagement*, c) *ecological validity* and d) *negative effect* whilst using COFFEE (refer to Section 5.7 for further details).

The SUS was specifically chosen for this study as the usability assessment tool for the following reasons: *a)* it is one of the most popular and reliable instruments used by HCI researchers for assessing perceived usability (Lewis, 2014; Lewis, 2018); *b)* extant research has shown that SUS has a high degree of reliability (Cronbach's alpha coefficient exceeds 0.8) and validity (Peres *et al*., 2013); *c)* there are several ways of interpreting SUS data owing to the extensive normative studies using this instrument (Bangor *et al*., 2009); and *d*) SUS can be used on a small sample size with reliable results when compared with other usability assessment tools (Tullis and Stetson, 2004). ITC-SOPI (Lessiter *et al*., 2001) was chosen specifically to measure the perceived SoP, as it is the most validated and prominently used questionnaire evident in the literature to measure the SoP of users (Busch *et al*., 2014; Usoh *et al*., 2000; Brade *et al*., 2017) and produced reliable results (Brade *et al*., 2017).

Qualitative interviews were also conducted with 15 out of 26 FFE experts who agreed to participate in an open-ended interview to obtain further options (Table 5.1). Since applications such as COFFEE as a virtual collaborative tool for communication of design is unique and new to the FFE literature, this uniqueness and newness supported the selection of a qualitative method, as suggested by Amaratunga *et al*. (2002). The selection of a qualitative method aided in the thematic analysis of the responses which provided further insight into the stakeholders' perspectives on COFFEE. While open-ended interviews are time-consuming and labour intensive, they provide an opportunity for the participants to express their views about COFFEE using their expression and terms thus providing a more personal and genuine perspective (Mills *et al*., 2010). Convenience sampling (Etikan, 2016) combined with a snowballing technique (Lewis-beck *et al*., 2004) was used to recruit the participants for this study because of the peculiarity of the study and the need for participants with expert knowledge of the FFE design related task. Gogtay and Thatte, (2016) suggested that convenience sampling combined with a snowballing technique enables researchers to invite participation from a few but most relevant, subjects. Participants for this study were invited using the researcher's social network (LinkedIn and email) and the participation was voluntary.

5.5. Development of COFFEE

5.5.1. Overview of System Architecture

Given the great potential of the application of VR in the FFE sector, there is a pressing need to address the technical limitation that restricts the ability to access a collaborative virtual environment in which a group of geographically remote stakeholders can interact, communicate effectively and asynchronously to appraise designs collaboratively in real-time. COFFEE harnesses a scalable, low-latency, cross-platform cloud-based server which aids in connecting remote users in the virtual environment, the Unity game engine to facilitate a high fidelity virtual environment that enables human-computer interaction (HCI) and a BIM authoring tool to develop the data-rich FFE design. Figure 5.2 shows the system-level details of COFFEE which consists of: 1) BIM module, 2) game engine module 3) distributed module and 4) users. Modules (1) to (3) ensure a seamless flow of design information to the users (4). The BIM model developed using the BIM authoring tool was exported into the game engine using Unity3D's native plugin called Unity Reflect (Unity3D, 2021) in an FBX file format. The model was retextured using a material enhancer application to yield a high visual fidelity. Furthermore, interaction, locomotion, avatar customisation and synchronisation over the network using remote procedure call (RPC), animation and multi-user communication over the network were enabled within the game engine. The developed virtual environment was compiled into an executable file (*.exe*) and an android application package (*.apk*) for multi-platform deployment. User login functionality was provided so that users could enter the collaborative environment with their name tags on the avatar (Figure 5.6) which would help co-users to identify each other whilst using COFFEE. After login in with usernames, each user will be directed to a lobby where they have the opportunity to choose their avatar (refer to section *5.6.3.5* for avatar customisation details). Once the user is happy with the avatar, they can choose the design space they want to review using the interactive option provided in the lobby. The following section provides further details about COFFEE components.

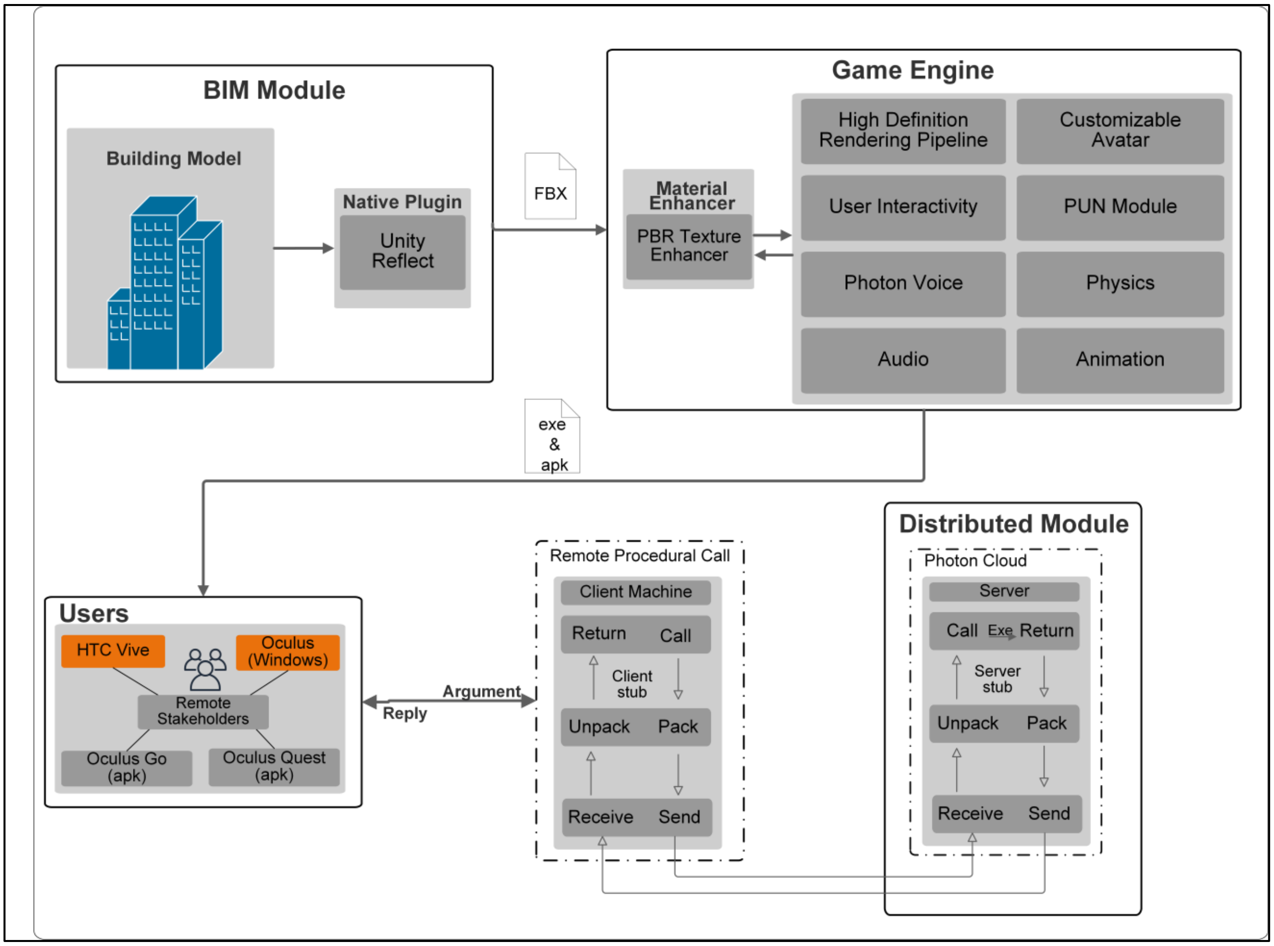
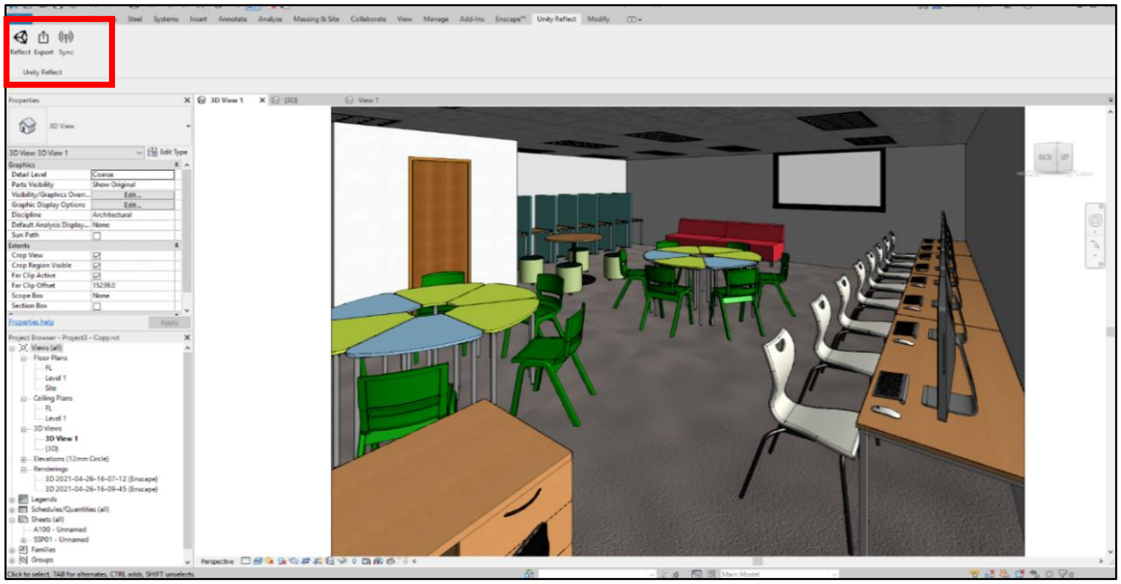


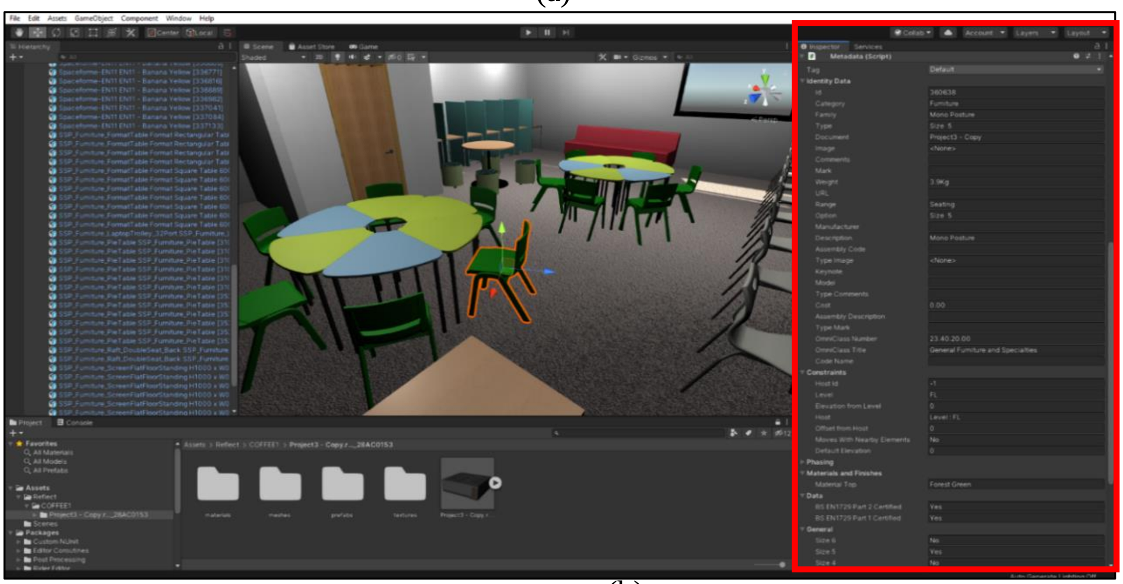
Figure 5.2: System architecture

5.5.2. BIM

The 3D model for COFFEE was developed using the BIM authoring tool Autodesk Revit (Autodesk, 2021) which acted as the data source for the proposed system. For this study, two FFE environments *1)* classroom and *b)* science lab for a school were developed for design review using COFFEE. All the required metadata for the FFE design review were attached to the FFE elements modelled in the authoring tools by creating required parameters and linking them to the FFE elements. While the stakeholders interacted with the FFE elements, this information was presented in the VR environment on a user interface (refer to Section 5.6.3.2 for details of the user interface). This made it possible for concurrent stakeholders to manipulate the FFE elements based on various parameters such as dimensions, materials, cost, warranty etc. Furthermore, Unity3D's native plugin "Reflect" (Unity3D, 2021) was used (Figure 5.3) as the interoperability enabler which served two critical functions in the development of COFFEE; *a)* Meta-data translation from the BIM authoring tool to the game engine; *b)* BIM model optimisation before being imported to the game engine. One of the major roadblocks that existed until recently was the interoperability issues between the BIM authoring tools and game engines, such as Unity3D (Du *et al*., 2018). Even though BIM authoring tools like Revit can generate FBX files that can be imported directly to a game engine, the metadata translations were resource-demanding and not straightforward. It has been observed in some studies (Lehtinen, 2002; Du *et al*., 2018) that there is no streamlined process for importing or exporting geometry between CAD software and game-engine. Further, previous studies (e.g., Yan *et al*., 2011) highly emphasise the need for middleware applications such as Autodesk3D's max for the metadata translation. Even though this workflow has eased the flow of the BIM model into the game engine without data loss, the iterations required in this process are comparatively cumbersome. Further BIM model optimisation process aided in reducing the number of polygons present in the BIM model, thereby eliminating the computational load of the graphic rendering, and eliminating possible frame rate drops and network delays. Eliminating possible frame rate drops and network delays is critical for any networked VR environment such as COFFEE because these performance drops can have a negative impact on the synchronisation of the stakeholder interaction in VR, resulting in a poor user experience that can affect the user's acceptance of VR technology (Brunnström *et al*., 2020).



(a)



(b)

Figure 5.3: (a) Unity Reflect Native Plugin within Autodesk Revit, (b) FFE Model in Unity Game Engine with Meta-Data Attached.

5.5.3. Game Engine

Unity3D was used as the virtual environment development platform that facilitates HCI in COFFEE. Along with the game engine module, this layer consists of a material enhancer component called Quixel Mixer (Quixel, 2021) that aided in the development of a high-fidelity virtual environment.

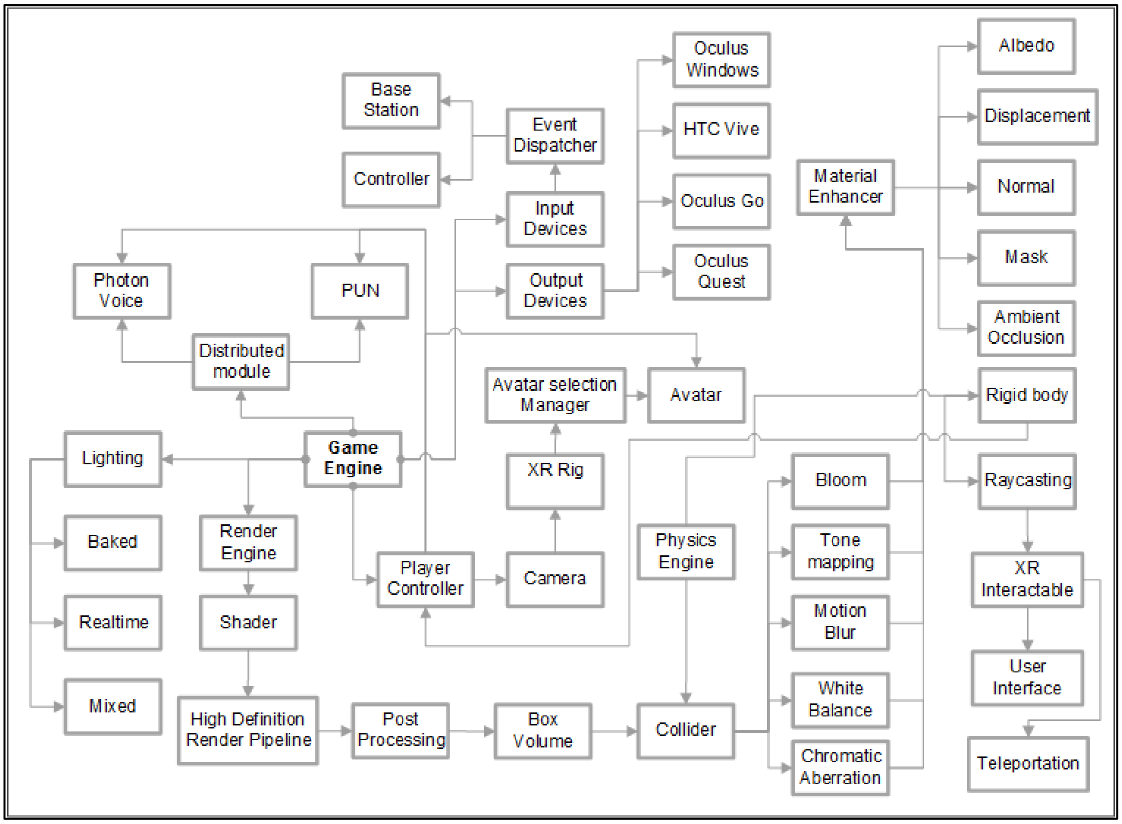


Figure 5.4: Game Engine Components

Figure 5.4 illustrates the game engine components. The below sections provide further details about the core components of the game engine.

5.5.3.1. High Fidelity Virtual Environment Using Material Enhancer and HDRP

Fidelity is a general and useful concept for characterising different VR frameworks, which Meyer *et al*. (2012) referred to as "*a measure of the degree to which a simulation system represents a real-world system*". Cooper *et al*. (2018) suggested that the effectiveness of the virtual environment is often measured through the assessment of fidelity. In various studies (Ragan *et al*., 2015; Slater *et al*., 2009), it has been noted that the visual fidelity of the immersive virtual environment has a positive impact on the user's performance and can trigger realistic responses in the user. Thus, visual fidelity has a significant impact on the FFE stakeholder's design decision, as aesthetic merit is most valued during an FFE design appraisal (Yoon *et al*., 2010). However, achieving such a higher level of visual fidelity in the virtual environment is a resource-demanding task, as it is necessary to re-texture the materials of the model imported from the BIM authoring tool. Ragan *et al*. (2015) noted that photo-realistic texturing is an effective way of providing a high-fidelity virtual environment. To streamline the workflow of photo-realistic texturing, Unity3D's high-definition render pipeline (HDRP) offers a scriptable render pipeline along with a material enhancer application, called Quixel Mixer (Quixel, 2021) was used. Figure 5.5 illustrates an example of a material conversion process using the texture mapping of the Revit model imported to Unity3D. This material conversion process using the texture mapping of the Revit model imported to Unity3D was applied to all the FFE elements to achieve a high visual fidelity as shown in Figure 5.5. One of the challenges faced during the process of texture mapping was the incompatibility between Unity3D's HDRP and the VR integration package, which failed to identify the material of the VR controllers. To overcome this challenge of the incompatibility between Unity 3D's HDRP and the VR integration package, which failed to identify the material of the VR controller, a custom shader graph was developed using Unity3D's shader builder, which was then applied as the controller's default shader graph.

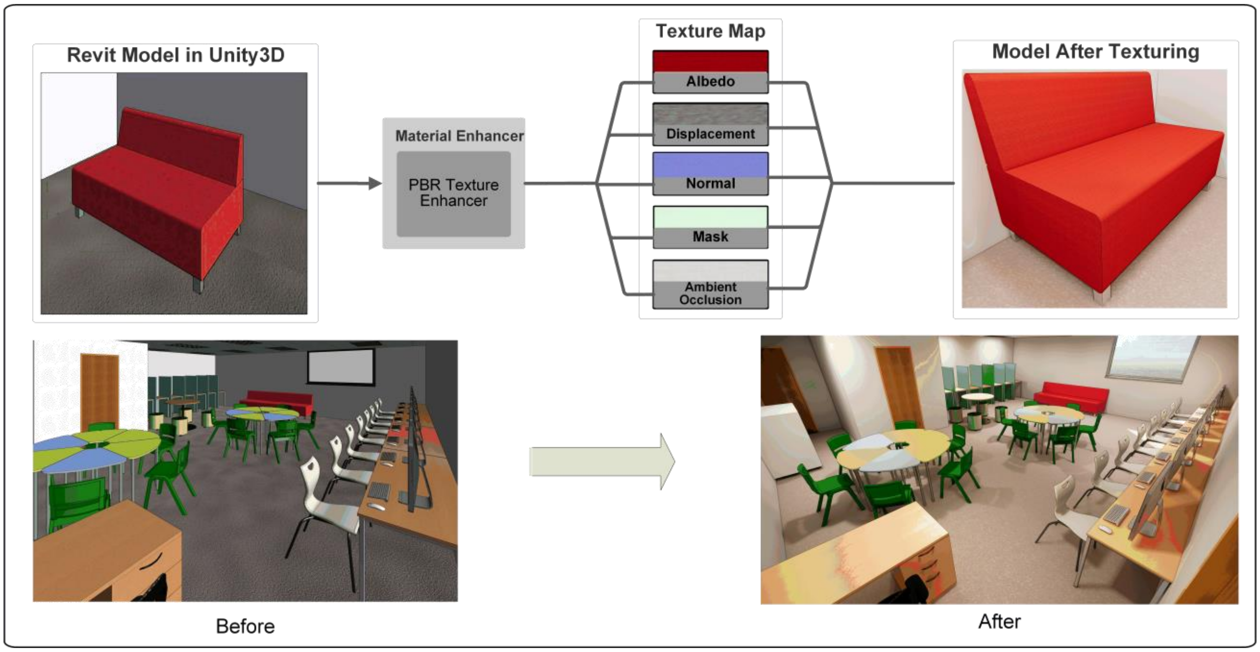


Figure 5.5: Re-Texturing Revit Model in unity using PBR materials (Classroom Model)

This process was important as the current study utilises a hybrid type of user interface that is virtually connected to the controller in the virtual environment.

5.5.3.2. Interface and Interaction in Virtual Environment

Winestock (2018) noted that developing a user interface that can immerse the users at the same time which will not have any negative effect on the task at hand and the experience of the users is one of the challenges VR developers always face. To overcome this challenge, a hybrid user interface that replicates a digital display with an interactive interface, namely, a virtual handheld tablet display is used (Figure 5.6) which is novel in the FFE literature. For the current study, a similar user interface was developed because of its novelty and ease of use. The interface provided an opportunity for the users to manipulate the FFE attributes such as material, texture, cost, and dimensions using the raycast functionality provided on the right-hand controller. These changes were synchronised over the cloud-based server so that co-users were able to visualise the design choices simultaneously.

(a)

(b) (c)

Figure 5.6: (a) Stakeholders (avatar representation) engaged in Classroom Design Communication, (b and c) Stakeholders (avatar representation) collaboratively deciding the science lab countertop finish.

For the current study, Unity3D's XR interaction toolkit was used because of its cross-platform VR controller input. Since COFFEE was developed for multi-platform deployment, the XR interaction toolkit aided in streamlining the development without focusing much on the type of head-mounted display (HMD) used.

5.5.3.3. Movement in the Virtual Environment

Two types of locomotion methods *a)* natural locomotion and *b)* virtual locomotion were provided in COFFEE for the users to choose based on their comfort. The most common way of virtual locomotion used is teleportation because of its ease of navigation and most importantly it is safer for the users (Boletsis and Cedergren, 2019). Also, teleportation is the most acceptable navigation method chosen by the users; as natural locomotion, tends to evoke insecurity and motion sickness in the users (Boletsis and Cedergren, 2019). However, COFFEE included both methods of navigation in the environment to understand whether FFE stakeholders make different choices while in a collaborative virtual environment.

5.5.3.4. User Representation in the Virtual Environment

User representation or self-avatar in the virtual environment is thought to have a significant impact on the user's experience in the virtual environment and to affect users' interaction in a collaborative virtual environment such as COFFEE (Pan and Steed, 2017). Further, the finding of Dodds *et al*. (2011) suggested that user representation in a multi-user virtual environment can enhance users' communication. Thus, in the current study, an avatar that was controlled dynamically by head and hand controllers, which were synchronised across the network, was used so that the transforms of each user in the environment were visible to other users. Also, users had the opportunity to choose the avatar's appearance based on their preference using the avatar customisation option provided on the virtual interactive display (Figure 5.7). A simple avatar representation with head and hand movements was used in COFFEE because, in studies such as those carried out by Lugrin *et al*. (2015), it was observed that the realism of the avatar in the virtual environment has no effect on the user's task and it was suggested further that simplistic avatar representation is best for faster and more economical development owing to the lower demand on computational resources. It is worth noting that since COFFEE was developed for a multi-platform deployment (HTC, Oculus Quest etc.), computational resources demanding elements that had no effect on the task were deliberately avoided. The avatar asset of Ufuk, (2020) was used for the current study because of its simplicity and ease of integration.

Figure 5.7: Avatar customisation

5.5.4. Distributed Module

The distributed module is the multi-user enabler in the COFFEE system where it synchronises the users’ transforms and the actions relating to design coordination and aids in transmitting voice communication between the users over the network through a scalable, low-latency network. COFFEE utilises the Photon network engine which is a widely used multiuser cloud server (Du *et al*., 2018). Once the users establish the connection over the network, their transforms and all actions in the virtual environment were synchronised by calling the remote procedure call (RPC)

(Figure 5.2). Furthermore, users were able to communicate whilst in COFFEE through a voice chat functionality that was implemented over the cloud network using photon voice.

5.5.5. Users

The geographically distributed users of COFFEE consisting of FFE's stakeholders (Architects, Designers, Contractors, Suppliers, Manufacturers and Client/End-users) are connected using HMD. COFFEE is a multi-platform compatible application, which means it can run on various types of HMDs (e.g., HTC Vive, Oculus Quest). This functionality was very important as Windows-based HMDs like HTC Vive are not very economical because of the additional cost of high-end computers as well as the requirement of bigger dedicated physical space because of the tethered connection with the computer. On the other hand, HMDs like Oculus Quest which are comparatively cheaper to procure have built-in processors due to which they are tether free and do not require a high specification computer. In the next section, a framework for integrating COFFEE and Scrum is detailed.

5.5.6. Integrating COFFEE and SCRUM for Lean Construction

Similar to other sectors of the AEC industry, one of the main challenges that FFE stakeholders face while designing a space is to account for the unforeseeable issues, risks and stakeholder requirements iteratively (Oh *et al*., 2010). As indicated by Streule *et al*., (2016) as an example, templates, checklists and simulations are used to reduce these unforeseeable risks in a sequential manner. However, the sequential approach requires a considerable amount of resources even before the actual construction starts. Streule *et al*., (2016) observed that it is often necessary to revise plans and drawings significantly by the time construction projects start as a result of modification to project requirements, which can result in cost overruns, schedule delays and low product quality. For a sector such as FFE that operates on narrow profit margins and tight project schedules, the consequences of these unforeseeable issues can have a huge impact on the quality and the sustainability of the sector. In this context, agile project management (APM) methods such as Scrum have proven to be an effective approach to mitigating the uncertainty in a construction project through promoting pragmatism in the organisation, increasing the flexibility of the process and valuing the collaborative work of the human team (Buckl *et al.*, 2011; Zender and Soto, 2021). Among several APM methods, Scrum is based primarily on the process of evolutionary planning and iterations and is one of the most accepted development models because of the opportunity it provides for incremental development of the design that makes it possible to assimilate the changes and fine-tune diversions regarding the expected objectives leading to the continuous development of the project (Rubin, 2012). Importantly Scrum seeks to continue project evaluation and adaptation through rapid stakeholder feedback (Zender and Soto, 2021). Further, Scrum works well when the number of stakeholders involved is small, project delivery time is short and high stakeholder interaction and satisfaction are key. These factors encouraged the integration of COFFEE with the Scrum model for this study. Figure 5.8 illustrates a framework for integrating the Scrum model with COFFEE. The Scrum roles presented in Figure 5.8 consists of the *FFE Client/representative*, *FFE design team* and the *Scrum master*. This team is self-organised and cross-functional and all the design decisions are taken within this team who has all the competencies required for the project. The *FFE Client/representative* is responsible for maximizing the value of the project and is also in charge of creating, updating, and prioritising the *product backlog*. A *product backlog* is a prioritised list of various items (e.g., Floor plan, FFE models, FFE specifications, rendered views etc.) which are created during the *Kick-off* meeting. The *sprint backlog* contains items from the *product backlog* which are selected by the *FFE client/representative* and the design team. The items on the *sprint backlog* are those that the design team believes can reach a *state of done* during each sprint. During the *sprint planning* stage, the FFE design team considers the amount of work required for each item in the *product backlog* and prioritises them to form the *sprint backlog*. Once the *sprint planning* has been completed, the design team starts the development of the design using the *BIM authoring tool*. The developed model is then imported into the game engine to enable interactivity and multiuser functionality which constitutes the COFFEE system. Once the planned designs are ready, they are presented in the *daily Scrum* meetings.

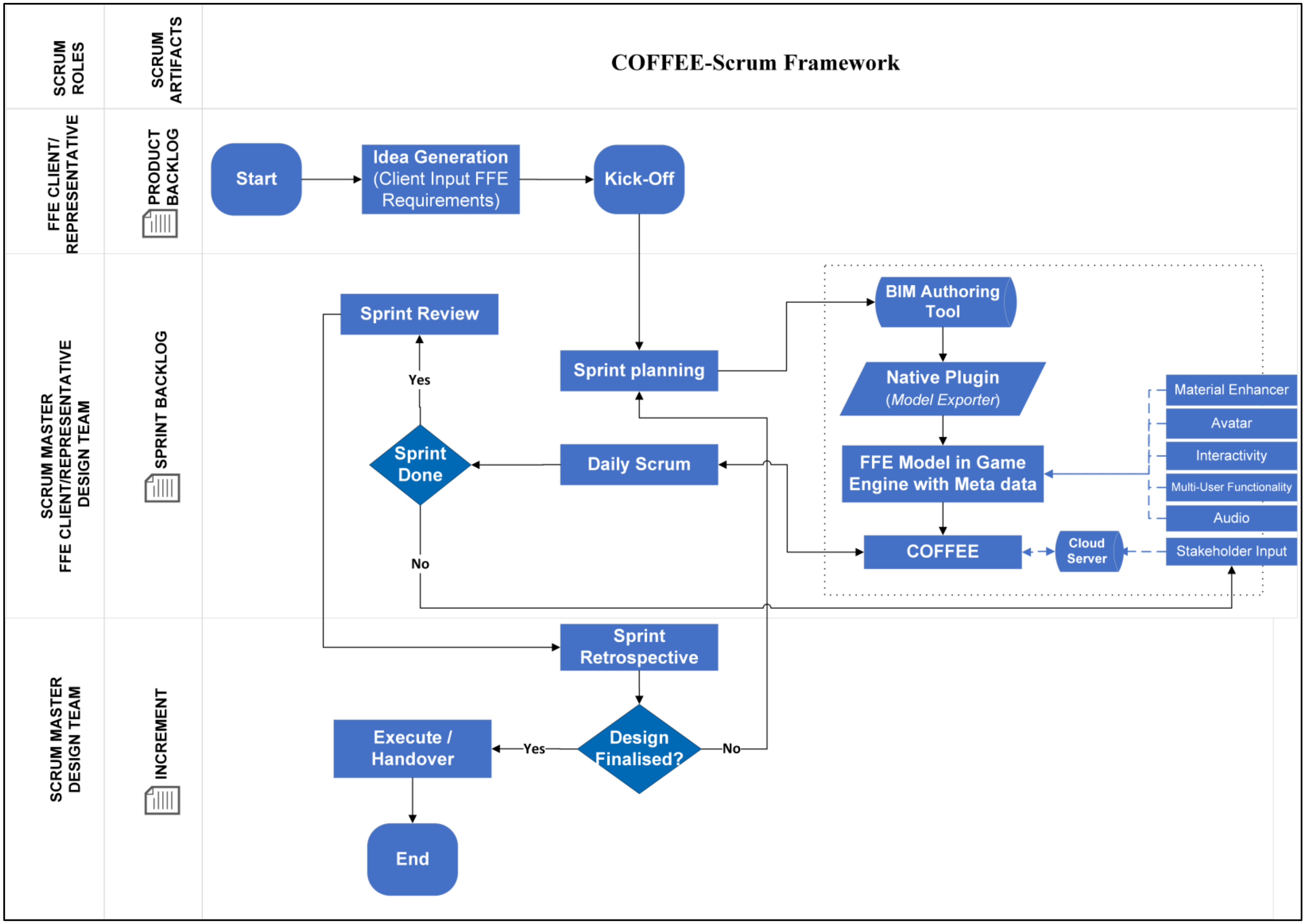


Figure 5.8: COFFEE and SCRUM framework

One of the benefits of integrating COFFEE with Scrum is that it enables remote collaboration among stakeholders during daily Scrum meetings. The iterations continue until the stakeholders are satisfied with the design. With the utilisation of COFFEE in Scrum workflow, the entire team is able to iterate the design instantaneously rather than re-planning the sprint. Being able to iterate the design instantaneously further reduces the time taken to achieve the milestones. Once the review of the planned designs has been accomplished, the progress made is reviewed in the *sprint review* stage, followed by the *sprint retrospective* meeting, which is held with all stakeholders to critically evaluate the process and the iterations made to the design. If the *FFE client/representative* is unsatisfied with the final design, then the sprint planning is repeated, and the process continues. Apart from the immersive, interactive and collaborative environment, the screen-short functionality offered by COFFEE to capture the design changes is highly beneficial for Scrum workflow. During the *sprint retrospective*, the stakeholders can utilise these design changes to critically evaluate the process and iterations.

5.6. Findings and Discussion

In the following sections, the findings from the testing and evaluation of COFFEE are detailed and discussed with reference to previous studies. Further, various aspects focused on the user's experience whilst using COFFEE were taken into consideration in order to provide a comprehensive assessment.

5.6.1. Testing and Evaluation

A series of usability trials were carried out using the SUS (Brooke, 1996) to test and validate COFFEE. Also, users' sense of presence whilst using COFFEE was assessed using the ITC-SOPI (Lessiter *et al*., 2001) focusing on the four sense of presence constructs. The trials for the current study involved 26 FFE stakeholders from a diverse age group. Detailed background information about the participants is provided in Table 5.1. Since COFFEE is a multi-user platform, the participants were invited for testing in groups of a minimum of two participants depending on their availability. However, the maximum number of participants in each group was kept to four based on the availability of the number of HMDs for trial. Before the trial, participants were asked to complete Section (A) of the questionnaire which elicited participants' background

information such as profession, age, gender, experience and previous experience using virtual reality. Participants were then briefed on the functionality of COFFEE and a short familiarisation with the user interface and other interactive functionality were provided. Each group was then given 15 minutes to test COFFEE for various tasks.

Table 5.1: SUS Score, participant's background information and ITC-SOPI Score

Participant ID	SUS Score	Gender	Age	Role	Previous VR Exp.	Mean Score SPS	E	EV	NE
PA 1**[**]**	67.5	M	57	FFE Contractor	×	3.88	3.75	3.66	1.50
PA 2[**]	67.5	M	63	FFE Manufacturer	×	4.5	4.50	4.33	1.00
PA 3[**]	82.5	F	33	Architect	√	4.16	4.25	4.33	1.00
PA 4	77.5	F	27	Architect	√	3.83	4.00	3.66	1.50
PA 5[**]	85	F	26	FFE Designer	×	4.33	3.75	4.33	1.25
PA 6[**]	75	M	29	FFE Designer	×	4.00	3.75	4.00	1.25
PA 7	77.5	F	37	End-User	×	4.33	4.00	4.66	1.00
PA 8[**]	82.5	M	29	FFE Contractor	×	4.33	4.00	4.33	1.25
PA 9[**]	70	M	27	FFE Contractor	×	3.83	3.75	4.33	1.25
PA 10[**]	87.5	M	29	Architect	√	4.16	4.00	3.67	1.25
PA 11	90	M	29	FFE Designer	√	4.16	4.00	3.67	1.50
PA 12	75	F	24	End-User	√	4.33	4.25	4.00	1.50
PA 13	90	F	27	End-User	×	4.32	4.00	4.67	1.00
PA 14	80	M	25	Architect	√	3.83	3.50	3.33	1.25
PA 15[**]	80	F	38	FFE Contractor	×	4.00	4.00	4.00	1.50
PA 16	77.5	F	28	FFE Designer	×	4.16	4.00	4.00	1.25
PA 17[**]	80	M	43	Architect	√	4.50	4.00	4.33	1.25
PA 18[**]	90	M	24	End-user	×	4.33	3.75	4.00	1.00
PA 19[**]	77.5	M	36	FFE Designer	×	3.83	4.25	4.33	1.25
PA 20[**]	92.5	F	46	Architect	√	3.83	4.00	4.00	1.25
PA 21	75	F	36	End-User	×	3.83	3.75	4.00	1.75
PA 22	80	F	26	End-User	√	4.50	4.25	4.00	1.00
PA 23[**]	62.5	M	51	Architect	×	3.83	4.00	4.00	1.75
PA 24[**]	65	F	53	FFE Designer	√	3.83	3.75	3.66	2.00
PA 25	85	M	26	End-User	√	4.66	4.25	4.00	1.00
PA 26	80	F	23	End-User	√	3.83	4.00	4.00	1.25
Average Score	78.95					4.12 (0.27[*])	3.98 (0.22[*])	4.05 (0.32[*])	1.29 (0.26[*])

It was suggested in previous usability studies (Bottani *et al*., 2021; Rahimian *et al*., 2019) that 15 minutes is a reasonable time for assessing the usability of technology. The group had the freedom to choose either of the design space options (Classroom or Science Laboratory). Even though there was no specific task to be completed, the members of each group were instructed to communicate their design ideas within the group and to finalise a design based on their discussion. Following the trial, participants were asked to complete Sections (B) and (C) of the questionnaire which consisted of ten SUS (Brooke,1996) and seventeen ITC-SOPI (Lessiter *et al*., 2001) questionnaires evaluated on a Likert scale with 1 = strongly disagree and 5 = strongly agree. The SUS score ranges from 0-100 with a 2.5 increment in steps, where the higher the score the better the perceived usability of COFFEE (Sauro and Lewis, 2016). The participants were also made aware that half of the SUS questionnaires would sound negative while the remaining half would sound positive and therefore, they should take care while completing the questionnaire. This awareness was important to ensure that the participants interpreted the questionnaire correctly, as the findings of Sauro and Lewis, (2011) indicated that approximately 13% of participants responded incorrectly to the SUS questionnaire because of the positive and negative tone. In addition, colour coding (green = positive and red = negative) was used to assist participants to identify the questions with negative and positive tones easily.

The perceived presence in COFFEE was assessed using the shortened version of ITC-SOPI with only the three highest loading items per scale, to have a more economical assessment of presence as suggested by (Busch *et al*., 2014), with 17 items instead of 44 items in the full version of the questionnaire. The four factors measured using ITC-SOPI were:

- *Sense of Physical Space* (SPS): is defined as "a sense of physical placement in the mediated environment, and interaction with and control over parts of the mediated environment" (Lessiter *et al*., 2001).
- *Engagement* (E): is defined as the "user's involvement and interest in the content of the displayed environment, and their general enjoyment of the media experience" (Lessiter *et al*., 2001).
- *Ecological Validity* (EV): indicates "the believability and realism of the content as well as the naturalness of the environment" (Lessiter *et al*., 2001).
- *Negative Effects* (NE): are "the adverse physiological reactions such as motion sickness, dizziness etc." (Mania and Chalmers, 2001).

Participants were then invited to participate in an open-ended interview to elicit further opinions about COFFEE. Owing to time constraints, 15 of the FFE stakeholders (Table 5.1) volunteered for the interview. In the next section, details of the findings from the usability and SoP test and the themes identified from the interview have been presented.

5.6.2. Reliability of Assessment Tool

The reliability of the assessment scale was calculated using Cronbach's alpha (CA). Reliability is the extent to which the instrument will yield the same result when the measurements are taken again under the same conditions. Brade *et al*. (2017) suggested that a CA higher than 0.70 for a questionnaire can be considered to be reliable. For the current study, the Cronbach's alpha for the SUS was 0.80 and ITC-SOPI was 0.75, which suggested that both questionnaires were reliable and had sufficient internal consistency.

5.6.3. Usability Evaluation

The SUS score for COFFEE is presented in Table 5.1. The computing of the SUS score was based on the recommendation by Brooke (1996). The mean SUS score obtained for the current study was 80, which was above the recommended threshold of 70, suggested by Bangor *et al*. (2009) and Brooke, (1996) for considering technology to be acceptable. Based on the adjective rating proposed by Bangor *et al*. (2009), the usability score for COFFEE fell between "good" and "excellent" (Figure 5.9) thus indicating that the stakeholders considered COFFEE to be easy to use, easy to learn and robust. In general terms, it was interesting to note that the four lowest scores (PA1, PA2, PA23, PA24) were from the participants who are above 50 years of age and some of the highest scores were from participants below 40 years, suggesting that the comparatively younger users were probably closer to technologies such as virtual reality, which was in line with the findings of Bottani *et al*. (2021).

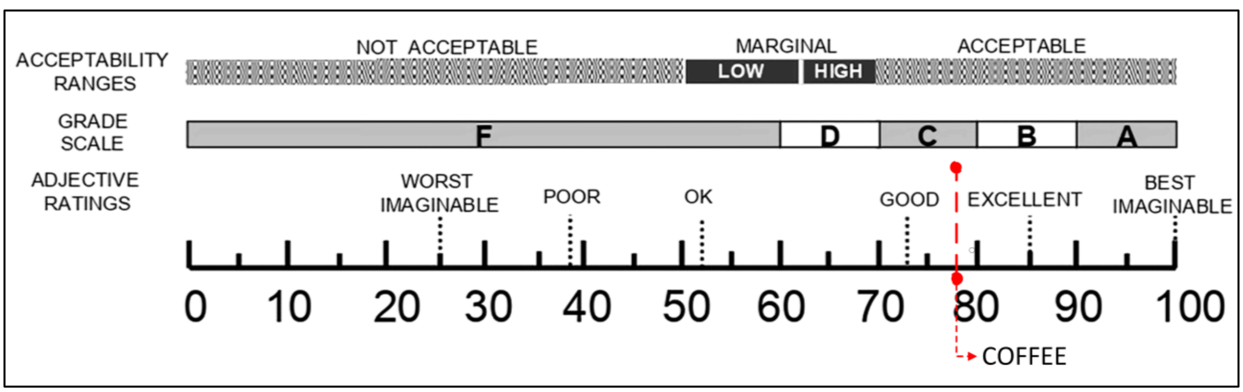


Figure 5.9: Grade ranking of SUS Score for COFFEE adopted from Bangor *et al*., (2009)

The low usability scores for participants (PA1, PA23, PA24) could also be attributed to their low level of sense of presence scores (Table 1) whilst in the virtual environment, which was in line with the findings of studies (e.g., Brade *et al*., 2017; Krassmann *et al*., 2020; Lorenz *et al*., 2018;

Busch *et al*., 2014) that suggested that the sense of presence in the virtual environment has a stronger connection with the usability of the system and will encourage the acceptance of VR technology. Furthermore, it is also worth noting that some of the highest scores were from the architects followed by FFE designers and contractors. The usability score for COFFEE indicated the acceptance of COFFEE by potential frequent users who found COFFEE to be useful and easy to use. Also, no significant differences in scores when compared with gender were identified ($p>0.05$). It has been noted in some studies (Lin and Chen, 2013) that gender differences affect the perceived usability of technology. However, Bangor *et al*. (2008) identified no differences in the rating of the usability of products based on gender, which was in line with the findings of the current study.

5.6.4. Sense of Presence

Table 5.1 provides details of the ITC-SOPI (Lessiter *et al*., 2001) scores for each of the SoP constructs, suggesting that COFFEE had no or very low, negative effect (NE) (1.30) as well as a high sense of physical space (SPS), engagement (E) and ecological validity (EV). The results from Table 5.1 suggested that the participants' SPS in COFFEE scored the highest score (4.12) which meant that participants had a higher feeling of “being there” while interacting with the FFE elements and the stakeholders. Further, the EV score was the second-highest (4.05) which suggested that the users felt that the virtual FFE environment delivered by COFFEE was sufficiently enough to replicate a response similar to the real-world environment. Furthermore, users showed good engagement (4.00) within COFFEE, which suggested good involvement and interest in the content delivered by COFFEE.

Further, Spearman's correlation analysis (Frey, 2018) was used to identify connections between SoP constructs and usability. To interpret the size effect (r) for significant effects and correlations Cohen's conventions (Cohen *et al*., 2013) were used. A value of ±0.10 represents a small effect, a value over ±0.30 a medium effect and a value over ±0.50 a large effect. An inverse correlation was identified for the usability and NE (r = -0.507, p= 0.008), which indicated that the usability of COFFEE can be affected by the negative effects caused by the VR environment, such as motion sickness, dizziness etc. This concurs with the findings of a previous study (Mousavi *et al*., 2013), which indicated that it is necessary to take utmost care during the process of VR environment development to reduce the negative effects of VE. However, the other three SoP constructs showed a low or insignificant correlation to usability. This contradicted the findings of Busch *et al*. (2014), using the CAVE environment, but supported the findings of Brade *et al*. (2017) using a real-world environment. It is worth noting that HMD based VR systems are capable of providing a more realistic and engaging experience than a CAVE system (Mallaro *et al*., 2017; Elor *et al*., 2020), which sometimes is sufficiently closer to a real-world environment, which suggests that, apart from the negative effects, no other SoP factors could potentially affect the usability of a system similar to COFFEE that provides a comparatively similar realistic and engaging experience to that of the real world.

5.6.5. Thematic Analysis of Expert Interview

The interview data collected were analysed using thematic analysis which is often referred to as the most efficient method in analysing qualitative data to capture valuable information (Braun and Clarke, 2006). In the current study, a six-phase analysis of the interview data was followed (familiarisation with the data; generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report). The main topics of the interview were to discover the usability of COFFEE for improving the FFE's workflow in the communication of design. The participants were informed fully about the research objective, consent procedure and confidentiality issues. The core questions used for the interviews were:

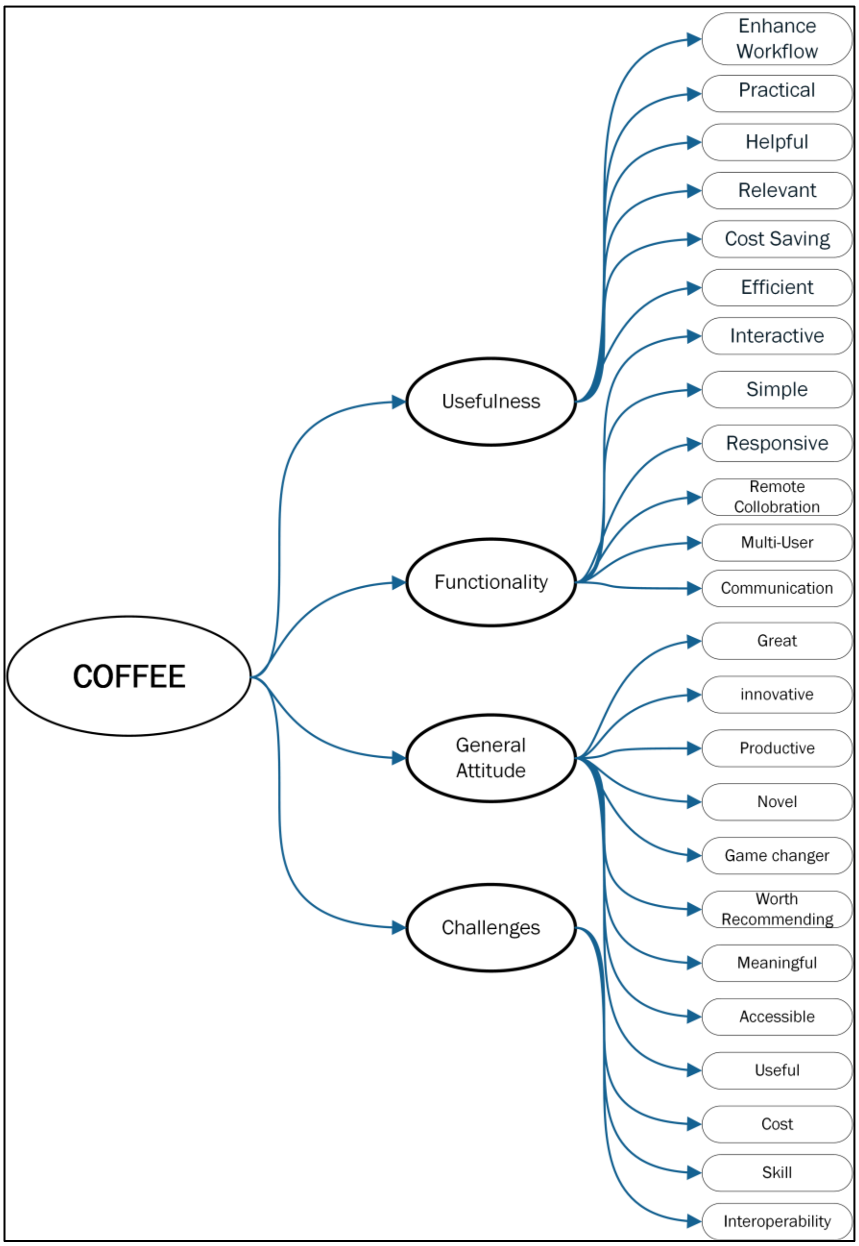


Figure 5 10: Themes identified from the expert interview

a) What benefits are you finding in the presented system when compared to the traditional design communication process existing in the FFE sector?
b) Do you think the level of functionality was appropriate for the FFE design tasks?
c) How can the tool be improved in your opinion?
d) What challenges do you think this system could pose for full-scale deployment?

In the sections below, each of the themes identified (Figure 5.10) has been detailed.

5.6.5.1. Usefulness

All the participants (n =15) considered COFFEE to be a useful tool to improve the FFE's communication of design. Participants (n = 3) pointed out that typically FFE's communication of design is a cumbersome process involving technical and non-technical stakeholders utilising mostly 2D-based designs that result in several design changes throughout the projects. However, with the utilisation of COFFEE in the FFE's design communication process, it is easy for all the stakeholders to be involved in the early design process, in an immersive environment providing them with the opportunity to understand the design, thus limiting costly design changes. One of the FFE experts commented:

> "Majority of our projects involve non-technical stakeholders who are unable to grasp the full design. We strongly believe that if we can utilise COFFEE in our workflow, we will be able to deliver an immersive design experience to our clients, at the same time utilise the multi-user functionality of COFFEE to take them through each element in the design as we do in a

> real-life walkthrough and finalise the design. This will reduce client disappointments, cost overruns due to design changes and importantly we can earn client trust."

This opinion of one of the FFE experts reiterates the finding of Schön, (1988), who noted that end-user/client and designers occupy an entirely different design world making design communication challenges. Based on the opinion of the FFE experts, COFFEE could be a game-changer in enhancing collaborative design communication with its stakeholders, regardless of their comprehension capabilities. This reiterates the findings of Chalhoub and Ayer (2018) and Du *et al*. (2018) who opined that the opportunity for early involvement of stakeholders (technical and non-technical) is one of the most important factors that encourage the adoption of distributed VR applications.

5.6.5.2. Functionality

All the participants (n = 15) commented positively about the various functionalities of COFFEE. Specifically, participants commented highly about the multi-user functionality which makes COFFEE unique from other VR-based design communication systems currently available. One FFE expert commented:

> "Our clients are spread across the UK, and it is sometimes hard for our team to be physically present for design coordination meetings. We think that multi-user communication functionality of COFFEE can be a game-changer in such situations".

Participants (n = 6) also mentioned the informative user interface of COFFEE. One participant commented:

> "The user interface of COFFEE is very simple, but it incorporates most of the information required for the FFE's client."

Participants (n=8) commented on the responsiveness of the interface and the method adopted to design it like a tablet interface. Two of the participants commented about the appearance of the avatar representation within COFFEE. One participant pointed out:

> "Avatar representation in COFFEE is a great way to improve user's involvement in COFFEE. However, it would be great if a full-body motion avatar which represents real humans could be incorporated to make the environment more realistic".

It is worth noting that in studies in which the influence of avatar realism on users' experience in the virtual environment was investigated (Heidicker *et al*., 2017), it was found that, motion-controlled avatars with less realism (similar to the one used for the current study) produced an increased feeling of co-presence as well as positive communication and interaction in the virtual environment. Also, since COFFEE was developed for a multi-platform (HTC, Oculus Quest etc.) deployment, elements placing demand on computational resources that had no effect on the task were deliberately avoided. Furthermore, all the participants (n = 15) opted for teleportation as the preferred means of navigation in the virtual environment, which was in line with the findings of Boletsis and Cedergren, (2019). One of the participants (P13) noted that nausea was experienced while using physical locomotion which led to switching to teleportation mode, which confirmed the findings of Buttussi and Chittaro, (2021).

5.6.5.3. General Attitudes towards Adoption of COFFEE

Further, all the participants (n = 15) showed a positive attitude toward the concept of COFFEE. Participants identified COFFEE as an innovative tool that could improve the productivity of the FFE sector. One participant commented:

> "This is a novel approach towards design communication. We work with a lot of elderly clients with physical and mental disabilities. With this technology, we can be in the same virtual environment with them guiding them through each design and finalising them based on their choice giving them full freedom of what they want without the isolated VR experience. We would like to utilise the possibilities of COFFEE for our upcoming projects".

Participants (n = 6) also mentioned that they would highly recommend COFFEE for use in their upcoming projects. Participant (P10) mentioned the possibility of demonstrating the potential of COFFEE to their clients so that COFFEE could be included in their projects for early-stage design. In a study by Mahamadu *et al*. (2022), it was noted that VR-based applications are highly efficient in supporting participatory design where views of elderly end-users are sought during the design process. However, one of the challenges of such VR applications is the feeling of isolation whilst in the virtual environment, especially when the users belong to a vulnerable population. In this context, the application proposed in the present study can eliminate these challenges through the sense of co-presence. Also, in general, Kim and Jo (2021) observed that co-presence in the virtual environment can highly improve the productivity and satisfaction of the design process and encourage the adoption of the application.

5.6.5.4. Challenges

FFE experts also noted some challenges that might constrain the full-scale deployment of systems similar to COFFEE. One of the critical challenges participants (n=8) were concerned about was the cost of adding virtual reality-based technology into the FFE's workflow. One participant commented:

> "Normally FFE contractors work with narrow profit margins which makes it difficult for small and medium enterprises like us to invest in VR related hardware, software and, importantly, the space required for setting up such systems."

It is worth noting that the challenge posed by the cost of VR has been reported by many studies (Garrett *et al*., 2018; Du *et al*., 2018). Although the recent advancements in hardware and software technology have made VR peripherals more accessible, it has been suggested that providing a high-quality VR environment still requires high-end computer systems with advanced processing units to run them, with additional application development costs (Garrett *et al*., 2018; Du *et al*., 2018). As with information technology, attrition of value is also rapid; older systems become obsolete with the rapidly emerging newer technology.

Also, the skills required for the development of a VR environment are another challenge that experts (n = 4) believed could affect the development and adoption of systems like COFFEE. As commented by an FFE expert above, the FFE projects operate mostly on narrow profit margins which limits them from recruiting developers solely for VR development. Adding basic programming modules to the construction education programme is a possible opportunity to develop professionals with multiple skills-sets which then would help sectors such as FFE to recruit multi-skilled professionals without incurring a financial burden. Furthermore, some participants (n = 4) identified interoperability as a challenge that could affect the adoption of such technology. Until recently, several iterations were required for the transfer of BIM models into the game engine which has been reported in several studies (Du *et al*., 2018, Chalhoub and Ayer, 2018). However, the recent integration of interoperability plugins like Unity Reflects (similar to the one adopted for the current study) is streamlining the data exchange process far easier than earlier. However, this also points toward the earlier cost constrain mentioned by the experts. Acquiring the licence for the development engine and interoperability tools can also add further costs for the FFE sector.

5.6.6. Comparison of COFFEE with Off-the-Shelf VR Platforms

Some of the critical functionalities and capabilities which make COFFEE superior to other off-the-shelf commercially available VR platforms including Mechdyne, World Viz, and WebVR are: a) COFFEE is primarily a BIM driven application that maintains a live link with the central BIM model through the Unity Reflect interoperability plugin. This live link with the central BIM model through the Unity Reflect interoperability plug-in will enable the stakeholders to update the FFE models in the game engine without having to reimport the affected elements, instead, any updates made on the central BIM model are synchronised automatically; b) along with delivering a compelling visual experience, COFFEE enables the stakeholders to visualise and interact with the important BIM metadata associated with the FFE elements. However, most of the off-the-self-applications available focus mainly on visual experience. The live link with the game engine and BIM authoring tool will allow the seamless synchronisation of any metadata updates like warranty, price etc. without having to undergo multiple iterations which could consume time and cost; c) COFFEE offers cross-platform capability ranging from high-performance VR devices to standalone medium-range VR devices without compromising the performance. However, off-self VR platforms mostly require high-performance devices for a seamless visual experience; d) finally, the system framework of COFFEE was developed by researchers from the AEC industry, focusing on keeping the front-end informative and intuitive, while maintaining a straightforward approach towards integration in the back-end, enabling stakeholders with varying technical capabilities to operate and maintain the system without having to invest in skilled manpower.

5.6.7. Implications

This study proposes a streamlined approach through the development and testing of a novel, collaborative, BIM-based distributed VR application for the AEC industry generally and the FFE sector specifically. This study has significant practical implications. The results of this study provide meaningful insights for guiding decisions in the development of distributed VR applications for the FFE sector. The distributed VR application proposed in this study was demonstrated to have a useability rating between good and excellent. This suggests that stakeholders considered the application easy to use and robust, which is critical for applications such as COFFEE. In a study by Wang *et al*. (2019), it was noted that applications with higher usability ratings tend to have a higher adoption rate. For a sector such as FFE which is on the path towards digitalisation (The British Furniture Confederation, 2018), a higher usability rating can have a positive impact on adoption. The development methodology proposed in this study will be particularly useful for the practitioner who designs BIM-based distributed VR applications for the FFE sector's use. Existing studies that demonstrate the integration of BIM and DVR indicate that the development of BIM-based DVR applications is challenging, cumbersome and time-consuming as they require multiple iterations and lacks a synchronised flow of information. A more streamlined approach is proposed in the present study toward integrating BIM and the distributed virtual environments with a synchronised flow of information. Furthermore, Song *et al*. (2021) observed that the sense of presence is an important mediating variable in the relationship between usability and efficiency. The assessment of sense of presence in COFFEE showed higher scores, indicating the usability and efficacy of the proposed distributed VR application for the FFE sector's use. A significant number of participants recruited for this study had more than 25 years of experience working as FFE designers and contractors in the FFE sector. For this reason, the findings of this study can be generalised and applied easily. This study can be applied, not only in many scenarios of the AEC industry but also to other industries such as the retail segment of the FFE sector, to develop distributed virtual FFE showrooms, as the development and testing presented in this study represent high ecological isomorphism. The present study also provides theoretical directions. The study highlights the importance of the sense of presence in influencing the usability of VR applications. Although the role of a sense of presence in a distributed virtual environment has been explored to build a robust body of literature on consumer satisfaction, physiology and training, few studies have tested the concept of presence and its relation to usability in the construction context. Furthermore, the concept of agile project management methods, such as Scrum, has been tested in a few construction literatures, albeit its integration with distributed VR environment has never been proposed. The framework proposed in this study will guide both academics and practitioners to integrate immersive VR applications with agile project management methods.

5.7. Conclusion

Like other sectors of AEC, collaborative design communication plays a crucial role in improving the FFE sector's performance and productivity. In recent years, the FFE sector has shown considerable interest in the utilisation of virtual reality for communicating design among its stakeholders because of its capability of delivering a strong feeling of presence and opportunity for immersive visualisation of design options on a true scale. However, existing systems have not been quite advanced in supporting distributed (multi-user) environments where stakeholders can interact communicate and appraise designs collaboratively in immersive real-time, while at different geographical locations. It was proposed in the current study that this shortcoming of the VR environment could be addressed, allowing concurrent multi-users to interact, communicate and collaborate virtually during design decision making in the FFE sector through the development of a collaborative FFE environment called COFFEE. COFFEE was tested among 26 FFE stakeholders (designers, contractors, manufacturers, architects and end-user/clients) to understand its usability and the experience of users whilst using COFFEE. Results indicate that COFFEE has a high usability index with an adjective rating between good and excellent. Further, users reported a high sense of physical space, engagement and ecological validity as well as very low negative effects whilst using COFFEE. Analysis of the usability and sense of presence factors revealed an inverse correlation between usability and negative effect. Further no or little significance existed between the other three sense of presence factors and usability scores. Thematic analysis of the qualitative interview with FFE experts (n=15) revealed that COFFEE is a highly useful multi-users

VR platform, which is a novel, innovative and productive tool for FFE's application. Experts also noted potential challenges (cost, skill and interoperability) associated with the full-scale deployment of COFFEE. In the current study, it was found that, in practice, COFFEE could be a highly useful tool to assist FFE's stakeholders to communicate design collectively at the early stage of the project.

However, it must be noted that, for industries to adopt a system like COFFEE, additional cost and skilled personal requirements need to be considered. Since COFFEE was developed to deliver a high visual fidelity experience, the hardware and software requirement to run such an environment are expensive. Also, the development of such a virtual environment requires skilled personnel, which adds to additional costs. The transfer of data for COFFEE from the BIM authoring tool to the VR development engine which has high visual fidelity that requires several middle-ware applications which also adds to the cost of development. For future development, the researchers will look into the integration of COFFEE with low-cost HMDs like Gear VR focusing on widening the accessibility of the application to all levels of stakeholders. However, this process might require limiting certain functionalities and visual quality of COFFEE for a smooth multi-user experience.

Chapter 6: Towards Development of a Distributed Virtual Furniture, Fixture and Equipment Shopping Environment

Abhinesh Prabhakaran[1], Abdul-Majeed Mahamadu[12], Lamine Mahdjoubi[1] and Colin A. Booth[1]

[1]Department of Architecture and the Built Environment, University of the West of England, Bristol, BS16 1QY, United Kingdom.

[2]Department of Construction Management and Quantity Surveying, University of Johannesburg, Johannesburg.

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Statement of Contribution: This conference paper is an empirical study which proposes a novel methodology for the development and testing of a distributed virtual showroom for showcasing FFE products. My contribution as the main author of this paper was to conceive the presented idea, development of the methodology, development and testing of the distributed virtual FFE showroom, analysis and discussion of the results, drafting of the paper and revising the paper based on the reviewers' comments. Co-authors of this paper are my PhD research supervisors who provided the mentorship, guidance, review of research concepts, methods and review of manuscripts. My overall contribution to this paper is estimated between 80-90%.

Abstract

The dynamic consumer behaviour, as well as the current state of nationwide lock-down and social distancing mandates, has left retail industries like the Furniture Fixture and Equipment (FFE) sector under unprecedented disruption, leaving them on the verge of collapsing. For the FFE sector to survive, they will have no choice but to adapt to new ways to get merchandise to their consumers. In addressing this gap, this study proposes a novel methodology for the development and application of a prototypical distributed virtual shopping environment (DVSE) that will allow furniture and fixture consumers to shop remotely in a fully immersive and interactive virtual environment, minimising the risk of physical contact but at the same time delivering a rich, meaningful, and compelling shopping experience. A two-phased approach involving furniture and fixture designers, retailers, architects and consumers (n=9) was carried out to ascertain the usefulness of DVSE. The first phase involved direct prototyping followed by testing of the developed system through demonstrations followed by interviews with FFE designers, architects' retailers, and consumers which allowed for the thematic analysis of the transcript. The key themes identified were further categorised based on the Technology Acceptance Model (TAM) constructs. Findings indicate that DVSE is a highly efficient and viable tool which can deliver a compelling and richer experience similar to an FFE in-store experience. It also revealed that the proposed system not only improves the sense of presence but also brings in a new dimension which is the sense of being together which has a positive impact on the user's purchase decision. Further, this study also revealed that the cost of the HMD as well as motion sickness as two critical factors that can hamper the full deployment of DVSE.

Keywords: Multi-user, Virtual reality, Furniture, Co-presence.

6.1. Introduction

The dynamic consumer behaviour, as well as the current state of nationwide lock-down and social distancing mandates, has left retail industries like the Furniture Fixture and Equipment (FFE) sector under unprecedented disruption, leaving them on the verge of collapsing. The recent advancements in digital information and communication technology (ICT) have eased the transition of other major retailer sectors from physical stores to online stores, thereby addressing this gap. Despite the exponential growth of online stores across various retail industries, for FFE retailers the pursuit of an online marketing channel has proved to be unsuccessful (Beele, 2015). A consequence of this is the significant risk of this sector falling into administration and subsequent employment losses. The relevance of reviving this sector cannot be overemphasised considering the contribution it makes to UK's GDP (£12.5 billion), the number of employments it creates in the UK (3,39,000) (The British Furniture Confederation, 2018), as well as UK governments plans to tackle the retail productivity challenge "*Fixing the foundation: Creating a more prosperous nation*" (HM Treasury, 2015).

Recently a number of studies have recognised the application of VR in the retail sector including the FFE sector, however much of these studies have devoted to the application of virtual reality with a focus on delivering an isolated virtual experience which is normally delivered in an in-store VR station, where the role of a sales advisor and family members in a collaborative purchase decision are completely ignored. Unlike other retail products, Ndubisi and Koo, (2006) identify FFE products as those items which require collaborative decisions between each member of the family with the assistance of a sales advisor before making a purchase decision. Further, a study by Lichfield, (2020) reveals that social distancing culture will be a part of the post-pandemic world, where people will have to radically change almost everything including the way they shop. This means the consumer will be less enthusiastic about in-store shopping. Mander, (2020) reiterates this and reveals that 50% of the consumers will be unwilling to visit physical stores in the post-pandemic world. Thus, there is a pressing need for the FFE sector to change its strategy to connect with the digital native of today by integrating the virtual and physical worlds by harnessing emergent technologies into their retail process. Thus the aim of this study is to propose a novel methodology for the development and application of a distributed virtual shopping environment (DVSE) for the FFE sector, that will allow FFE consumers to shop remotely in a fully immersive and interactive virtual environment, minimising the risk of physical contact but at the same time delivering a rich, meaningful and compelling shopping experience that will allow them to have a well-informed and collaborative purchase decision without visiting the physical store.

6.2. Decision-Making Behaviour in the FFE Sector

FFE products are often purchased for appeal as well as function. Several empirical studies (e.g., Kotler and Armstrong, 2003; Oh *et al*., 2008; Prabhakaran *et al*., 2021) have concluded that the FFE consumer's purchase decision is influenced by how well it blends with the architectural aspect of the building. Thus, the decision-making behaviour in FFE is a complex process involving the consideration of restraints such as cost, space availability, aesthetics and matching with the architectural aspects of the facility (Oh *et al*., 2008). Additionally, due to the significant expense and long product lifecycle of the FFE, consumers have to make difficult trade-off decisions with regard to critical factors such as style and functionality (Oh *et al*., 2008). Thus, the end product of such a complex decision-making process is the uncertainty arising among the consumers over whether they have made the correct design choice, keeping the consumers away from the FFE retailers or delaying their purchase decision (Oh *et al*., 2008). Further, studies (e.g. Kim *et al* 2013) points out that shopping experience and purchase decision are also influenced by social relation and individual perspectives. For example, consumers share their opinions about FFE products, solicit various opinions from their family and friends and have fun through their interaction with others of similar interest (Pfeiffer and Benbasat, 2012). Evans *et al*., (1996) suggest that purchase behaviour should be viewed through the lenses of social and relation behaviour, thus the role of family members and friends in a purchase decision is crucial. In this context, visual representation interactivity and importantly the opportunity of co-presence offered by DVS can play a critical role in assisting the consumers in having a well-informed decision before committing to a purchase.

6.3. Methodology

This study is built on a sequential exploratory mixed-method research strategy based on a ‘Pragmatic’ philosophical stance (Dudovskiy, 2018). A two-phase approach was adopted for this study, where the first phase involved the development of the prototypical DVSE system for the FFE’s application, based on direct prototyping methodology. Mahamadu *et al*. (2020) highlight the evidence of the growing use of direct prototyping as an application system design and development methodology in requirement elicitation during the development of an application, software or any human-computer interaction system where an iterative process is employed to interact with users. In the second phase, the developed system was subsequently tested among n=9 participants through demonstrations followed by interviews with FFE designers, architects' retailers, and consumers which allowed for the thematic analysis of the transcript. This will allow the researcher to identify the participant's view, opinion, and knowledge experience from the qualitative data as well as aid in summarising key features identified in the interview. A convenient sampling along with snowballing technique was used to recruit the participants for this study due to the peculiarity of the study and the need for participants with expert knowledge in the FFE design related task as proposed by Mahamadu *et al*. (2020). The sample size was deemed adequate on the basis of the sample size of similar experiments where the quality of the experiment process is the focus rather than quantity and generalisability which is the case of alternative methods such as surveys (Chalhoub and Ayer, 2018). The key themes identified were further categorised based on the Technology Acceptance Model (TAM) constructs. The rationale for using TAM constructs is solely based on its extensive use by empirical studies focusing on technical innovation in the retail sector (Pantano, 2014) which is often described as “the most influential and commonly employed theory of information systems” by (Lee *et al*., 2003). The ethical approval for this study was granted by the University of the West of England research ethics committee. The participants were detailed about the research objective, consent procedure and confidentiality of the data collected.

6.4. Proposed System Architecture and Development

In the first phase, three-dimensional (3D) models of FFE as well as the virtual showroom environment, were developed using the Building Information Modelling (BIM) authoring tool Autodesk Revit, which allowed for the development of fully parametric models. Further, to achieve a high-fidelity visual experience in the virtual environment, which has a profound effect on the user's experience, satisfaction and purchase intention (Song *et al*., 2018), it was necessary to use the Physically Based Rendering (PBR) method of shading and rendering which enabled an accurate representation of light interaction with the FFE products in the virtual environment. For this purpose, a middleware application called Materialize Bounding Box was used to create the texture maps. Further, Unity3D (Unity, 2020) game engine was used to develop the distributed virtual environment (DVE) and interactivity. The models developed using Revit were exported in Film Box (.fbx) format into the game engine to keep the model lightweight as well as to ensure faster file exchange in the workflow (Mahamadu *et al*.,2020). DVE was achieved through the implementation of the Photon networking module “PUN”, which is an independent networking engine and multi-user platform which is fast, reliable and importantly scalable (Photon, 2020). Further, networked voice communication that will allow users to interact within the virtual environment was achieved using Photon voice which can be scaled seamlessly and automatically in the photon cloud (Photon, 2020). The implementation of Photon modules (PUN and Photon Voice) which are hosted on a globally distributed Photon cloud, guarantees low latency and short round trip time for the users to transform synchronisation as well as voice communication. This is critical in the development of any multi-user platform, as latency can have an adverse effect on the user's experience and acceptance of the technology (Jackson, 2020). The developed application was provided with two FFE product segment options a) school and b) kitchen (Figures 6.1, 6.5 and 6.6). The interactivity in the virtual environment was mainly related to the manipulation of the FFE design including colour, cost, material and size. The immersive environment was developed for Oculus Quest HMD which requires an Android (.apk) build. This specific HMD was chosen for the study due to its compatibility, standalone capabilities, as well as inside-out tracking that, will allow precise synchronisation of the avatar's head, body and hand movement over the photon network. This also eliminates the need for a wall-mounted tracker as well as a high-performance computer.

Figure 6.1: Environment selection interface

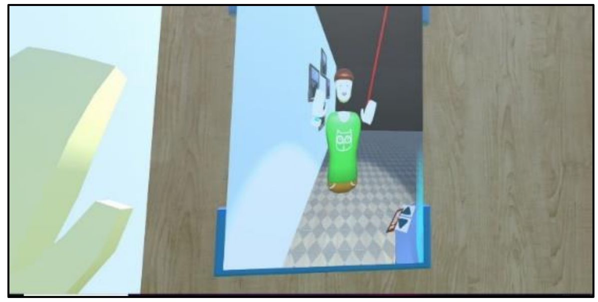

Figure 6.2: Users previewing selected avatar in a mirror

Figure 6.3: Avatar customisation pod

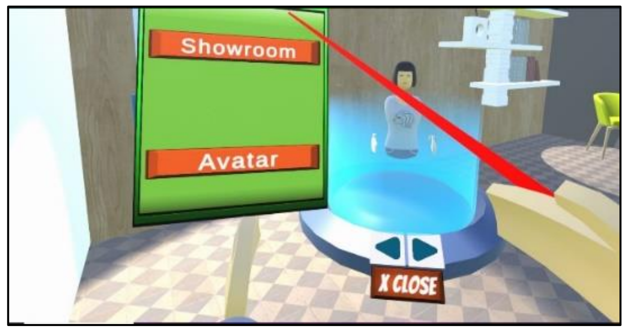

Figure 6.4: User interface

Figure 6. 5 Users exploring school furniture (FPV)

Figure 6.6: Users exploring kitchen furniture (FPV)

However, with the use of Photon networking, cross-platform deployment of the application is also possible if required in future for wider deployment. Further, users were provided with an opportunity to select their avatar preference (Figures 6.2 and 6.3), which represented the user's action in the virtual environment. Studies (Heidicker *et al.*, 2017) suggest that the avatar representation of users whose actions are synchronised over the Photon network can improve users feeling of co-presence and behavioural interdependency. This study utilised Ufuk, (2020)'s virtual environment assets (avatar and customisation pod) due to their simplicity and ease of integration. Further, two modes of locomotion methods were provided in the virtual environment a) Teleportation and b) Joystick movement. The participants were given the freedom to choose the locomotion method they prefer.

6.5. Testing of the Proposed System

A sample of nine (9) participants (architects, FFE designers, retailers, and consumers) ascertained the DVSE's acceptance. All the participants took part in the testing of the DVSE followed by a qualitative interview, where they had an opportunity to test the application in a fully immersive and interactive DVE. Further, direct prototyping aided in improving the system, as the feedback from the participants was incorporated in each stage of the development. The profile of the participants is provided in table 6.1.

Table 6.1: Participant's information

Participant Reference	Interviewee	Experience
P-1	Architect	2
P-2	Architect	4
P-3	FFE Retailer	28
P-4	FFE Retailer	25
P-5	FFE Designer	5
P-6	Care Nurse (Consumer)	3
P-7	Care Nurse (Consumer)	2
P-8	University Student (Consumer)	2
P-9	Architect	6

Further, a thematic analysis of the interview response was also employed to document participants' views in relation to the application's perceived usefulness, ease of application, enjoyment general attitude towards application and intention to adopt DVSE when commercialized. This also aided in the proposition of future consideration for research in this area.

6.6. Findings and Discussion

The thematic analysis revealed that all the participants (n=9) had a positive overview of the proposed application. The key themes identified are categorised based on the Technology Acceptance Model (TAM) constructs and are reported in Table 6.2. All the participants (n=9) considered the DVSE as practical, helpful and relevant for the FFE sector with regard to the PU construct. One of the participants (P-4) commented "We see this application (DVSE) as a very helpful tool for the FFE sector to display a large variety of our products without having to invest in showroom space and samples. This will save us from huge investments. This tool will be highly beneficial for our consumers as well to shop confidently". Further, a key finding from this study is that interactivity offered by DVSE has a significant impact on participants' responses. This finding is in agreement with the studies of Mahdjoubi *et al*., (2014). Participant (P-3) commented that "The interactivity offered by DVSE is capable for us to display a huge variety of our products, which at present is impossible for us".

Table 6.2: Thematic reviews of comments after practical testing of prototype

Theme of Participants' Comments	Summary of Participant Sentiments			
	FFE Consumer	Architects	FFE Designer and Retailers	Codes associated with responses and keywords
Perceived Usefulness for FFE needs (PU)	↑	↑	↑	Practical; Helpful; Relevant, Cost saving
Perceived Ease of Application (PEA)	↑	↑	↑	Interactive; Simple; Responsive;
Perceived enjoyment (PE)	↔	↔	↔	Exciting, Motion Sickness; co-presence
General Attitude towards application concept (GA)	↑	↑	↑	Great; Innovative; Efficient; Productive, Novel
Intention to adopt when the application is commercialized (AI)	↑	↑	↑	Worth Recommending; Useful; Meaningful; Accessible

(Key: ↑ - Positive; ↔ - Neutral; ↓ - Negative)

"This will be a huge cost saving for us and for the consumers we give an opportunity to visualise any product variant in an immersive environment and make a purchase with full confidence and satisfaction". Further, all the six participants who test the application considered DVSE as interactive: Simple, and Responsive. However few participants (P-1, P-2, P-6 and P-8) reported motion sickness while using the joystick locomotion method which reiterates the findings of (Mahamadu *et al*., 2020). All the participants (n=6) preferred teleportation as the preferred locomotion method. All six participants who used DVSE identified the avatar representation as a critical engagement factor that delivers a "sense of being" in the virtual environment. This concurs with the findings of Casanueva and Blake (2001) and Söeffner and Nam (2007). However, it contradicts the finding of Mahdjoubi *et al*., (2014), which suggests that avatars may not have any impact on the user's experience and engagement. This could be attributed to the type of virtual environment (exploratory VR) used for their study, which is incapable to deliver a sense of embodiment (Matamala-Gomez *et al*., 2019). Also, all the participants (n=9) commented on the multi-user functionality whose significance cannot be overemphasised where social distancing norms due to the COVID-19 pandemic. With regards to the GA construct all the participants (n=9) considered DVSE as Great; Innovative; Efficient; Productive and Novel. All Participants considered DVSE Worth Recommending; Useful, and Meaningful. One participant (P-4) commented, "We definitely would like to develop DVSE further to incorporate all our product range and to recommend to all our supply chain". However, two of the participants (P1 and P6) raised concerns about accessibility to VR HMDs. With the recent chip revolution and advancements in information technology, it is expected that in the coming years' extended technology peripherals will be more accessible to the general population (Dingman, 2020).

6.7. Conclusion

This study proposed a novel methodology for the development and application of a distributed virtual shopping environment (DVSE) for the FFE sector, that will allow FFE's consumers to shop remotely in a fully immersive and interactive virtual environment, minimising the risk of physical contact but at the same time delivering a rich, meaningful, and compelling shopping experience that will allow them to have a well-informed and collaborative purchase decision without visiting the physical store. The developed system was tested among architects, consumers, FFE designers and retailers to ascertain its usability. The findings from this study confirm that users responded positively to the DVSE. The key themes identified from this study were categorised based on the TAM constructs and are presented. The study also revealed that avatar and voice communication evoked voice evoked a sense of embodiment for the users and could potentially eliminate the isolated feeling of the virtual environment as identified by Mahamadu *et al*., (2020). It is worth noting that, for the FFE sector to adopt a system like DVSE, the additional cost of procuring hardware and software as well as skilled manpower requirements need to be considered. Further, at the time of this study, major interoperability issues existed between the BIM authoring tool and the VR development game engine (Unity3D) which has led to the utilisation of several middleware applications and iterations. This must be taken into consideration by the industry while implementing a system like DVSE. Future studies should consider exploring nonexperimental methodologies in a real-life FFE consumer set-up to understand the efficacy of tools like DVSE.

Chapter 7: Virtual Reality Utility and Usefulness in the Furniture Fixture and Equipment Sector: A Validation of Interactive and Distributed Immersion

Abhinesh Prabhakaran[1], Abdul-Majeed Mahamadu[23], Lamine Mahdjoubi[1], Colin A. Booth[1] and Clinton Aigbavboa[3]

[1]Department of Architecture and the Built Environment, University of the West of England, Bristol, BS16 1QY, United Kingdom.

[2] The Bartlett school of Sustainable Construction, University College London

[3]Department of Construction Management and Quantity Surveying, University of Johannesburg, Johannesburg, South Africa

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Statement of Contribution: This journal article is an empirical study which validates the utility and usefulness of the interactive and distributed VR applications developed for this research. This study further evaluates preconditions for the successful implementation of the developed immersive applications through experimentation. My contribution as the main author of this paper was to conceive the presented idea, development of the methodology and questionnaires, analysis and discussion of the results, drafting of the paper and revise the paper based on the journal reviewers' comments. Co-authors of this paper are my PhD research supervisors and collaborators who provided the mentorship, guidance, review of research concepts, methods and review of manuscripts. My overall contribution to this paper is estimated between 80-90%.

Abstract

Virtual Reality (VR) has proven to be an effective tool in improving the design communication of the Furniture, Fixture, and Equipment (FFE) sector. Although the FFE sector is well placed to leverage VR technology for competitive and operational advantages, the diffusion of VR applications in this sector has followed a steep curve. This study reports on the implementation of two novel VR applications in the FFE sector as well as investigates the challenges and benefits associated with their use and adaptability. The two applications trialled in this study were distributed VR and interactive VR for virtual collaboration in the selection of FFE components as part of the interior design process for building projects. A sequential exploratory mixed research methodology consisting of three phases was adopted for this study. This includes identification of VR implementation factors (Challenges and Benefits) using experiments with in-house prototyping of VR applications, rigorous literature review and questionnaire survey to solicit FFE Stakeholders' (n=117) opinion on the utility and usefulness of proposed applications as well as understanding factors that facilitate and inhibit their implementation in FFE context, particularly as design communication and coordination tool. The findings of this study revealed that distributed and interactive VR has become very central to digitalising FFE design communication with *Improved Design Communication* regarded as the most important benefit of its use. Conversely, the most critical challenge that inhibits the implementation of these two VR applications in the FFE sector is the *Perceived Cost.* This research provides an opportunity for the FFE sector to better understand the challenges that could restrain the full-scale adoption of VR into FFE's work follow as well as aid them in devising mitigation plans for future adoption. Further, this study also unveils the benefits that will allow this sector to embrace VR technology to improve the workflow. This study provides valuable insight to FFE's stakeholders to devise action plans to mitigate myriad complex and interrelated factors that affect the adoption of virtual reality technology in the FFE sector that

are otherwise very hard to understand, and the consequential implementation of any mitigation plans cannot be devised.

Keywords: Virtual reality, Challenges, Benefits, Adoption, Construction, Furniture, Fixture and Equipment

7.1. Introduction

With the advanced capabilities of immersive and interactive visualisation, Virtual Reality (VR) is dramatically changing the way humans interact with visual information. This potential of VR has attracted the attention of researchers from various sectors of the Architecture Engineering and Construction (AEC) industry, including the Furniture, Fixture and Equipment (FFE) sector. The FFE sector often communicates its designs with its stakeholders using traditional methods such as two-dimensional drawings/sketches (2D) and brochures (Prabhakaran *et al*., 2021). It has been noted in previous studies that the design decisions of stakeholders are strongly affected by the aesthetics of the FFE element and how well it blends with the architectural aspects of the building (Pakarinen and Asikainen, 2001; Prabhakaran et *al.*, 2021). Thus, aesthetics plays a vital role compared with other criteria such as cost and functionality (Creusen and Schoormans, 2005). However, Prabhakaran *et al*. (2021) suggested that the traditional methods of design communication in FFE (paper-based or 2D-based) are unable to deliver a complete understanding of this aspect to the FFE sector's stakeholders which has resulted in costly reworks, time overruns and poor stakeholder satisfaction with the end product (The British Furniture Confederation, 2018). A consequence of this is the significant risk of this sector being unable to meet stakeholder requirements which might lead to low demand and even a decline in productivity. The relevance of reviving this sector cannot be overemphasized considering the contribution it makes to the UK's GDP (£12.5 billion) and the number of employment opportunities it creates in the UK (The British Furniture

Confederation, 2018).

Recently, as the utilisation of building information modelling (BIM) became prominent in the AEC industry (Kamari *et al.*,2022), the FFE sector embraced these data-rich three-dimensional (3D) models to communicate its designs (Cotey, 2017). However, Walasek and Barszcz, (2017) noted that the complexity of current building designs was causing information latency in non-technical FFE stakeholders who are unable to comprehend such complex 3D designs on a 2D interface (i.e. computer monitor), thus making the design communication process more challenging and cumbersome. In this context, it has been proven in various studies that the utilisation of virtual reality in the FFE sector for design communication and coordination can improve the stakeholder understanding of the design dramatically and their satisfaction with the design being proposed (Fadzli *et al*., 2020; Yoon *et al*., 2010). Roy and Tai, (2003) and Zhang *et al*. (2019) observed that the visual representation, resulting immersion, and the interactivity offered by VR play a critical role in the FFE's design communication. Similarly, Yoon *et al*. (2010) also concluded that VR can greatly assist design communication in the FFE sector. Cumulative evidence suggests that the application of VR in the FFE sector has immense potential to enhance communication and coordination of design through immersive visualisation and interaction. Although the FFE sector is well placed to leverage this technology for competitive and operational advantages, the diffusion of VR applications in this sector has followed a steep curve. Despite the investments (£ 72 million) and promotions by the UK Government to encourage the adoption of VR technology in the AEC industry (Gov.UK, 2018), being a low technology-oriented sector, the FFE has fallen behind in embracing VR (The British Furniture Confederation, 2018). This could be attributed to a myriad of complex and interrelated factors that are very difficult to understand and the consequential implementation of any mitigation plans cannot be devised. To this end, the purpose of this study was to investigate these factors namely the benefits that facilitate and challenges that limit the adoption of VR in the context of FFE. There were four objectives for this study: 1) Ascertain the industry-wide usefulness of the single-user interactive and distributed VR applications developed for the FFE sector's use; 2) Identify the most relevant benefits that facilitate increased utility, usefulness, and adoption, and identify the challenges that inhibit implementation of these applications in the FFE sector; 3) Categorise the factors to ascertain the most critical components and dimensions; 4) Drawing upon the categories of drivers and challenges, explore what various determinant antecedent conditions influence and how they facilitate or inhibit implementation and use in various FFE contexts, particularly for design communication and coordination.

7.2. Literature Review

7.2.1. Virtual Reality

The term virtual reality was coined in 1989 by Jaron Lanier to distinguish the immersive digital world and traditional computer simulations (Pimentel and Teixeira, 1993). In recent years VR has evolved rapidly attributed to its flexibility in being adapted to different problems and domains which has led to different interpretations of a virtual environment (VE). Oxford dictionary defines VR as "The computer-generated simulation of a three-dimensional environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment such as a helmet with a screen inside or gloves fitted with sensors". Virtual environments of varying immersions and capabilities can be achieved using various types of VR technologies (Spaeth and Khali, 2018). These levels can be divided generally into three categories (Figure 7.1): *a*) Passive *b*) Exploratory, and *c*) Immersive VR (Pimentel and Teixeira, 1993). Passive VR refers to spectator activities such as watching TV whereas exploratory VR involves interactively exploring a 3D environment on a 2D interface such as a monitor (Pimentel and Teixeira, 1993). However, "immersive VR is the classic stage of VR, users can fully interact with the VE, stimulating all the senses and have their actions directly affect the computer-mediated environment" (Lingard, 1995) This computer-mediated environment is an umbrella term to summarise VR Mixed Reality (MR) and Augmented Reality (AR). Figure 7.2 presents the Reality-Virtuality continuum (Milgram and Colquhoun, 1999) which ranges from entirely virtual to entirely real thus entailing all possibilities in between.

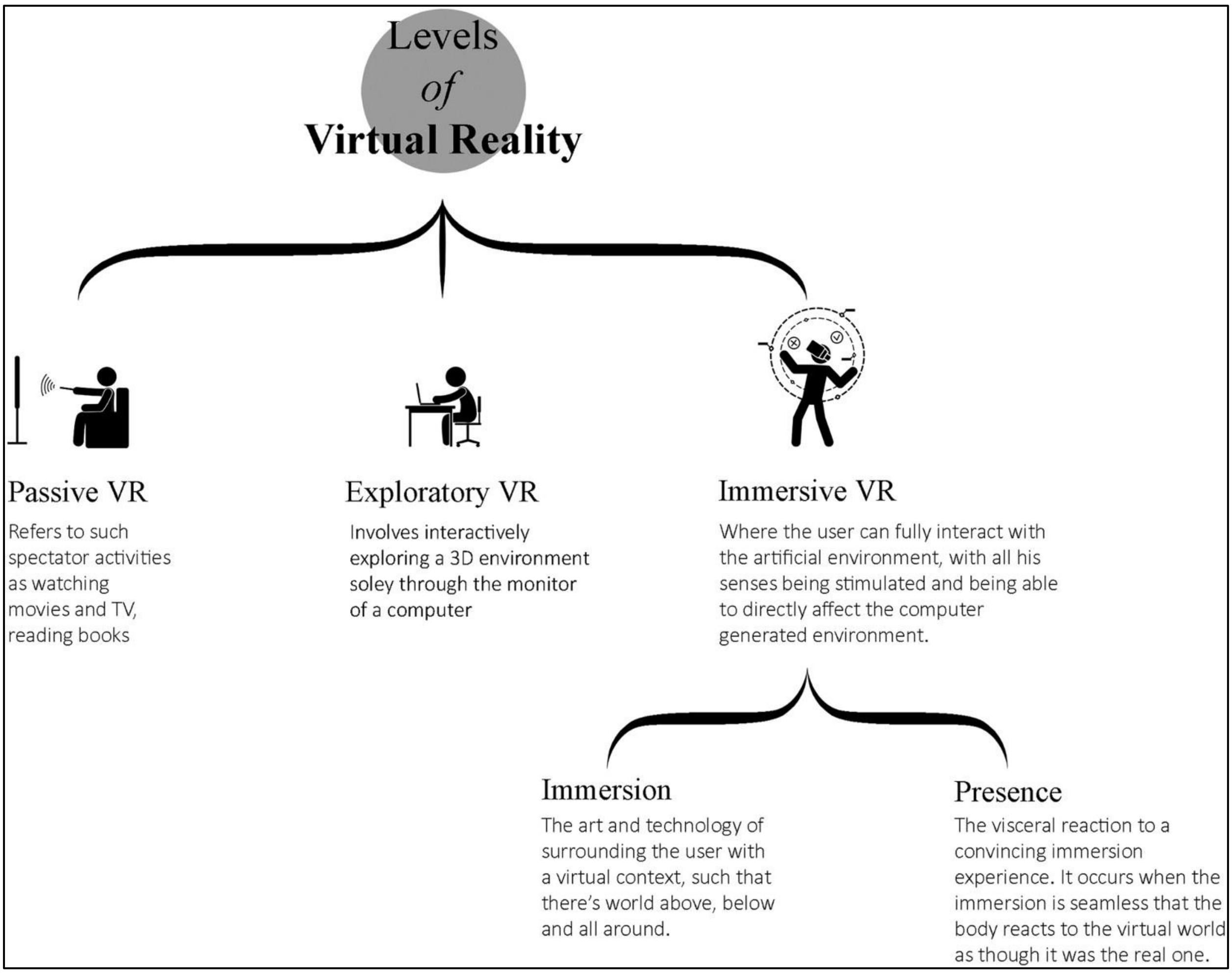

Figure 7.1: Levels of virtual reality (Spaeth and Khali, 2018)

In the present study, the third category described as immersive VR facilitated by a head-mounted display is the main focus and was used for the experiments detailed in section 3.4. In the immersive VE, the ultimate objective is to achieve maximum immersion, by providing the feeling of "presence" which Slater (1996) defines as the "Subjective experience of being in one place or environment, even when one is physically situated in another". Thus, it aims to provide the users with a sense of "realness" in a VE. A variety of VE enabling devices are used in present architecture and construction practice. The VR hardware can be broadly divided into two categories, Immersive Dome Display (IDD) also known as CAVE VR and Head-mounted Display (HMD) (Woessner and Kieferie, 2016). Although CAVE VR systems can provide 180 to 360-degree view angles and can accommodate multiple users at the same time (Manjrekar *et al*., 2014), they are less interactive for individuals than HMD based VR systems as the users share a common scene in the CAVE VR, where every individual user shares the same perspective, movement and interaction as noted by (Spaeth and Khali, 2018; de Freitas *et al.*, 2022).

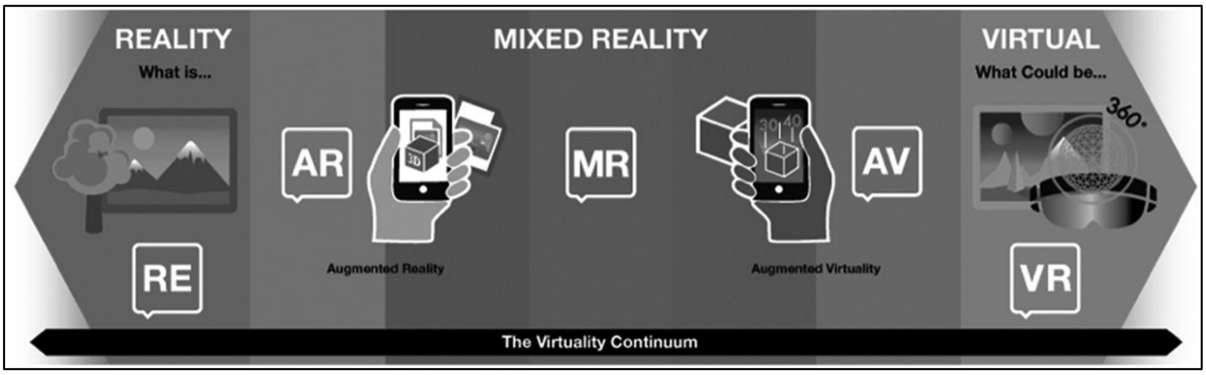

Figure 7.2: Reality virtuality continuum (after Milgram and Colquhoun, 1999)

HMD-based VR is used to facilitate a truly immersive environment, using a true, stereoscopic, 3D display projected onto both eyes of the users (Shen and Grafe, 2007). Modern-day HMD comes with different functions and capabilities ranging from tethered HMDs to untethered

HMDs. Tethered HMDs require a physical link to high-performance computers allowing them to process high fidelity VE, whereas untethered HMDs are self-contained VR devices which has self-contained processers thus eliminating the need for external processers. This also improves user mobility and eliminates safety concerns of trips and falls while using tethered HMD devices. However, these self-contained VR HMDs are limited in their processing capability, thus utmost care is required to optimise the VE content for optimal performance. Prabhakaran *et al*. (2021) and Mahamadu *et al*., (2022) emphasized the need for an optimised VE for reducing frame rate drops, which can have a negative impact on the user's experiences such as motion sickness and nausea.

A VE can be interactive or non-interactive depending on the task at hand. Creating a non-interactive VE does not require specialist knowledge. This is specifically advantageous in the AEC industry as the contemporary construction practice has expertise in creating three-dimensional models as the construction sector has now embraced BIM as noted by Woessner and Kieferie, (2016). The BIM to non-interactive VR workflow is now much straight forward through the utilisation of software such as Enscape (Enscape, 2022), which does not require additional skills, thus eliminating the cost associated with training or recruiting a multi-skilled workforce. On the other hand, creating an interactive VR requires additional programming skills. However, software such as Unity Reflect (Unity Reflect., 2019) has eliminated the interoperability issues that existed between BIM and VR development software like Unity (Unity3D, 2020). This has also streamlined workflow allowing construction practitioners to transfer the BIM model directly from the BIM authoring tools such as Autodesk Revit (Autodesk, 2019) into game engines such as Unity3D without losing the BIM meta-data. These advancements are encouraging the AEC industry to reap the full benefit of VR. A BIM to unity workflow is presented in Figure 7.5.

7.2.2. Virtual Reality in the AEC Industry

Over the past decades, VR has been explored increasingly by researchers from the built environment Adekunle *et al*. (2021). This could be attributed to the fact that the built environment is intrinsically linked to 3D space and this industry relies heavily on imagination for its design communication (Davila Delgado *et al*., 2020). The application of VR in the AEC industry can be traced back to the early 1990s when it gained the attention of architects, who garnered the interest of the other sectors of the AEC industry. Berg and Vance, (2017) noted that the current state of VR was "mature, stable and importantly usable" in the AEC industry. This was attributed to the recent advancements in hardware and software that have rendered the application of VR worthwhile. VR has been identified as one of the major technologies that are contributing to the digitalisation of the construction sector in the Fourth Industry Revolution (Industry 4.0) and represents a major innovative technological tool that can enhance the current design communication between AEC's stakeholders, which is referred to in Gartner's hype cycle as the "plateau of productivity" (Padilla *et al*., 2018). This is reiterated by the UK's Data for Public Good Report (NIC, 2017) in which VR is considered to be a key technology for enhancing the productivity of infrastructural delivery. The application realm of VR in the AEC industry belongs to a wider spectrum. For instance, recent advancements in eye-tracking technology have encouraged researchers to use VR in combination with eye-tracking technology to achieve greater insights into human visual behaviours and cognitive processes, which are impossible to elicit using subjective measures. Some of the notable researchers in this area include Shi, Du, and Ragan (2020); Shi, Du, and Worthy (2020); and Jeelani *et al*. (2020). These studies point out that the utilisation of VR in conjunction with eye-tracking technology enables the simulation of construction environments to be realistic enough to induce responses by the users that are similar to real life. This unique feature of VR has also gained the attention of researchers seeking to enhance construction safety training, where placing human participants in real-world construction hazard scenarios is risky and practically impossible (Yap *et al*., 2021). Some of the other well-explored areas in the utilisation of VR include design communication (Klerk *et al*., 2019; Kang *et al*., 2010; Wolfartsberger, 2019), lighting design (Zhang *et al*., 2019), construction scenario evaluation (Fu and Liu, 2018) facility management (Shi, Du, and Worthy, 2020), construction training and education (Boakye *et al*., 2021).

Klerk *et al*. (2019) utilised VR to assist in decision-making during the early stage of design ideation and the findings of the study showed that VR can assist stakeholders greatly by making effective design decisions easier, satisfying, and more efficient than computer-aided design (CAD) tools. Similarly, Du *et al*. (2018) and Tea *et al*. (2022) developed a multi-user VR environment that enables collaborative design communication utilising the BIM meta-data protocol. The purpose of the study was to address the isolated VR experience, which was one of the most reported shortcomings of VR applications (Mahamadu *et al*., 2022). Du *et al*. (2018) showed that co-presence in VR can enhance stakeholder communication and design decisions made. The potential of VR has also been tested in the real estate sector to understand potential homebuyers' emotions and purchase intentions (Azmi *et al.*, 2021). The results of this study indicate that VR can evoke pleasure and emotional arousal similar to that of a real-world environment. The results further indicate that VR can be used as an alternative to real-world scenarios which can induce better purchase intentions among consumers. VR has also been proven to be an effective tool in understanding wayfinding behaviour and emergency evacuation which has been explored by Lin *et al*. (2020). Thus, the application of VR in the AEC industry belongs to a wider spectrum that has been explored by researchers, proving that VR is a viable and productive tool for the AEC industry. While the benefits of the application of VR in the construction industry are extensive, it is acknowledged that several challenges impede the wider adoption of VR technology in the AEC industry.

7.2.3. Virtual Reality in the FFE Sector

Since space is a finite resource, it is imperative that all stakeholders involved understand, communicate and collaborate effectively to yield high quality and optimised output (Roupé *et al*., 2016). This imposes a huge responsibility on the designers, as the end-users will spend most of their time (90%) living with the FFE elements, which should be functional, comfortable, and pleasing (Ergan *et al*., 2019). Thus, planning and designing the FFE elements in a facility require utmost care and detailed attention. The FFE sector utilises 2D-based methods such as orthographic projections (i.e., floor plans, section elevation), brochures, and realistic renderings to communicate its design. While realistic images have certain benefits such as communication improvements, fluid development of FFE design ideas, and problem detection at the early design stage (Kuhlo and Eggert, 2013), they lack depth and spatial perception which makes the process less intuitive for the stakeholders (Carrasco and Chen, 2021). Similarly in the case of 2D drawings, one of the major challenges in processing graphical information is that the FFE design might be well-intended, but the messages conceived by the stakeholders might differ from the original intended message because of the noises created during the encoding and decoding of the communication process (Dadi *et al*., 2014). This process becomes more cumbersome and inefficient resulting in poor stakeholder engagement when the actors involved are non-technical and lacks design comprehension skills (Ganah, 2003). Since the seminal work of Schön, (1988) it has been widely acknowledged that the designers and non-technical stakeholders, especially end-users occupy an entirely different design world, which makes design communication even more challenging. The introduction of BIM has led to a paradigm shift in design communication in the FFE sector where data-rich

BIM models aided in communicating the design with stakeholders of all levels more effectively (Prabhakaran *et al.*, 2021). However, recent building designs have become more complex than ever, making it difficult to comprehend the 3D design viewed on a 2D interface such as a computer monitor (Prabhakaran *et al.*, 2021; Zaker and Coloma, 2018). Further, this type of design communication process also requires costly FFE prototypes for the stakeholders to finalise the design. This imposes a huge cost on the FFE sector which often worked on narrow profit margins. Recently the researchers have focused their attention on utilising the unlimited possibilities of immersion and interaction offered by VR in design communication and collaboration in the FFE sector.

Mahdjoubi *et al*. (2014), in their study, presented an interactive real-time simulation for house products using a desktop-based (exploratory) VR system which aimed at assessing the effectiveness of virtual FFE showroom on stakeholder's cognitive and affective response. In particular, their study investigated the consumer's response to real-time simulation using humanoid avatars when compared to response without avatars in an attempt to address the importance of human presence to assist consumers during a purchase decision. The results of the study revealed that interactive VE is highly beneficial for FFE stakeholders even though the presence of an avatar had no significant effect on the stakeholder's decision making. In another study, oh *et al*. (2004), proposed a web-based desktop VR (exploratory) system to assist FFE stakeholders during the purchase decision of home furniture. In their study, they used interactive 3D models to assist the stakeholders to select the configuration, and other aesthetics features like colour, texture, material etc. to assist them during a purchase decision. In 2008, the same authors used this web-based VR (exploratory) to compare its efficacy with two (2D) dimensional static image-based systems. Their study results demonstrate that enhancing stakeholders' ability to visualise the furniture products has significantly positive differences in their product experience and decision making. Zenner *et al*. (2020) in their study used a fully immersive VR to allow the customers to elaborate on different configurations of furniture whilst the sales expert modified the configuration. In their study, they also used passive haptics to allow the consumers to experience a realistic tactile feeling while in the VR. Their study revealed that a VR configurator is a viable tool as it can assist the stakeholder in making a purchase decision. Prabhakaran *et al*. (2021) used virtual reality to assess the effectiveness of immersive VE for FFE design communication compared to 2D based method. Their study noted that stakeholders had higher satisfaction with designs communicated using a VE. Some of the other most notable studies which have explored the utilisation of VR in the FFE sector are Bahri *et al*. (2019); Ding and Wang (2007); Fadzli *et al*. (2020); Forbes *et al*. (2018); Freitag *et al*. (2018); Janusz (2019); Moparthi *et al.* (2020); Niu and Lo (2020); Oh *et al.* (2004); Prabhakaran *et al*. (2021); Yoon *et al*. (2010).

Cumulative evidence suggests that VR is a viable and worthwhile technology for application in the FFE sector that can drastically improve the efficiency of this sector by enhancing design communication and collaboration. However, despite the proliferation of research in this area, a very low level of uptake in the industry has been witnessed. This could be attributed to a myriad of complex and interrelated factors that must be addressed if the adoption of this technology is to become easier and smoother.

7.3. Research Methodology

A sequential exploratory mixed research methodology (Saunders *et al.*, 2015) which combines qualitative and quantitative data collection and analysis was employed in a three-phase design. This method was chosen because it allows the exploration of concepts through qualitative methods and subsequent testing of assumptions using quantitative study. Figure 7.3 illustrates the framework of this study, which consisted of three phases. In the first phase, two experiments and a systematic literature review to identify the key factors (Challenges and Benefits) that affect the adoption of VR applications. While the two experiments were focused specifically on understanding factors contributing to adoption in the FFE sector, the systematic literature review focused on eliciting factors from the AEC industry as a whole due to the limited number of literature that focuses on the application of VR in the FFE sector. The details of these experiments and systematic reviews have been discussed in Section 3.4. In the second phase of the study, a questionnaire survey (discussed in Section 3.3) was administered to solicit the perceptions of FFE stakeholders of the factors affecting/facilitating the implementation of VR in the FFE sector using a five-point Likert Scale ranging from Strongly Disagree to Strongly Agree. In phase 3 of the study, the factors identified were categorised into components that determine the intention to adopt VR technology in the FFE sector. Based on these components of benefits and challenges, how various antecedent conditions affect the intention to adopt VR based tools for design communication and coordination in the FFE sector was determined using inferential statistics.

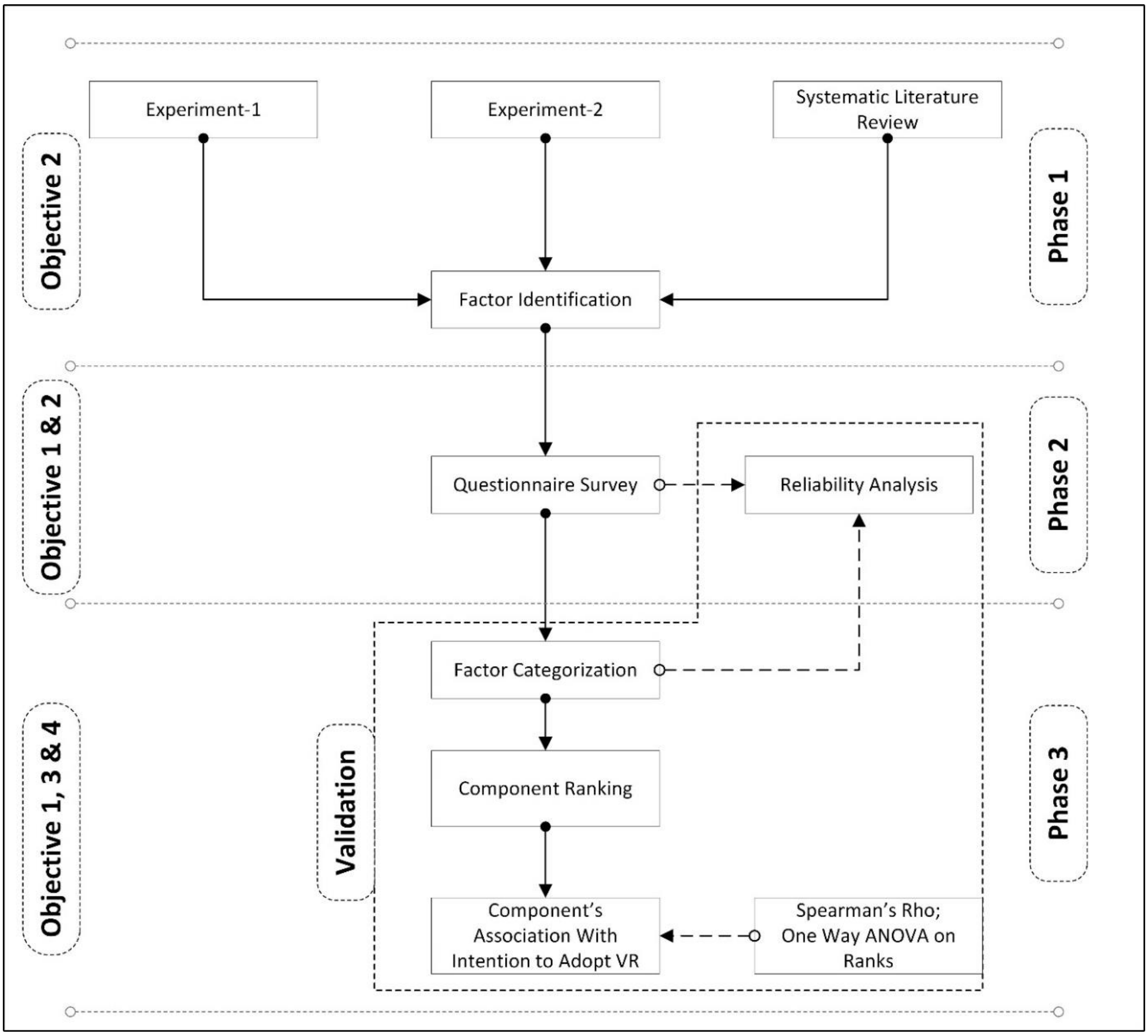

Figure 7.3: Research framework

7.3.1. Respondents Selection

The participants for this study included FFE stakeholders (architects, FFE designers, BIM coordinators, FFE consultants, and interior designers). The distribution of the participants is shown in Table 7.1. A non-probability sampling method (purposive and snowball sampling) was used to target potential participants for this study. Purposive sampling involves actively choosing participants who would be able to provide the best response to the survey questionnaire. Also, using snowball sampling aided in obtaining participants that were otherwise difficult to identify using purposive sampling. This combination of sampling methods made it possible to identify the maximum number of potential participants. The questionnaire was distributed to 183 FFE stakeholders and 117 completed questionnaires were received, which represented a 64% response rate, which is a typical response rate in construction management surveys (Mahamadu *et al*., 2017).

Table 7.1: Demographic characteristics of respondents

		Frequency	Percentage	Cumulative
Profession	Architect	42	35.90	35.90
	FFE Designer	21	17.90	53.80
	BIM Coordinator	24	20.51	74.40
	FFE Consultant	8	6.80	81.20
	Interior Designers	22	18.80	100
Gender	Male	77	65.80	65.80
	Female	40	34.20	100
Age	20-30	45	38.50	38.50
	31-41	51	43.60	82.10
	42-52	20	17.1	99.10
	>51	1	0.90	100
Construction Industry Experience	1-4	38	32.500	32.50
	5-10	47	40.20	72.60
	11-20	25	21.40	94
	>20	7	6	100
Previous Virtual Reality Experience	Yes	73	62.40	62.40
	No	44	37.60	100

7.3.2. Methods and Statistical Tests

A combination of descriptive and inferential data analysis techniques was employed to assess the survey respondent's perception of the factors that could affect their organisations' ability to implement VR. Descriptive statistics were used to summarise the characteristics of the data.

Kruskal-Wallis ANOVA and Spearman's correlation analysis were used to gain detailed insights into the relationship between the factors affecting/facilitating VR implementation and the intention to adopt VR-based applications in the FFE sector. To validate the internal consistency of the questionnaire results, a reliability analysis (Cronbach's alpha) was carried out. All the analyses were performed using the Statistical Package for Social Science SPSS 25.

7.3.3. Development of the Survey

In phase two of the study, a questionnaire survey consisting of two sections was used to solicit the perception of FFE stakeholders regarding the factors that could affect/facilitate the implementation of VR in their organization. The purpose of the first section of the questionnaire was to capture background information of the participants, the level of usage of digital technologies in the participants' organisations, and their intention to adopt and invest in VR technology. This section of the questionnaire also included video demonstrations of two VR applications developed for experiments one and two (described in Sub-Section 3.4.1 and 3.4.2) to solicit participants' opinions about the utility and usefulness of these VR applications in the context of FFE. Section 2 of the questionnaire, which consisted of 58 implementation factors (33 challenges and 25 benefits) was intended to obtain the perceptions of FFE stakeholders about factors that could affect and favour the implementation of VR in the FFE sector. A five-point Likert Scale ranging from strongly disagree to strongly agree was used in this section. The pilot testing of the questionnaires was carried out with twelve experts (five from the FFE sector, three VR-related application developers and four architects) to ensure the clarity, structure, and logic of the questionnaire. Qualtrics was used to develop the survey and survey links were distributed using social networking platforms such as LinkedIn as well as emails to professional networks.

7.3.4. Identification of VR Implementation Factors in FFE

The factors affecting and facilitating VR implementation in this study were identified using a systematic literature review and two experiments using VR applications developed for use in FFE. In the following sub-sections, each of these methods is explained further and Tables 7.2 and 3 show the lists of factors identified.

7.3.4.1. Experiment 1-Interactive VR for FFE's Design Communication

Rapid development in ICT, especially in VR, has contributed to new opportunities to address the communication and engagement gap in the FFE sector, which has offered a reliable extension of BIM for more advanced visualisation and communication (Rasmussen *et al*., 2017). However, there were very few examples of the application of VR in the FFE sector, and reports have highlighted some limitations of the current application of VR in the FFE sector as merely an over-glorified extension of traditional 2D communication. Thus, the full potential of data-rich BIM models integrated with VR has not yet been realized to its fullest extent. In bridging this gap, this experiment explores the effectiveness of an interactive immersive VR environment in enhancing the stakeholder's communication and resulting understanding of an FFE product design choice for a facility.

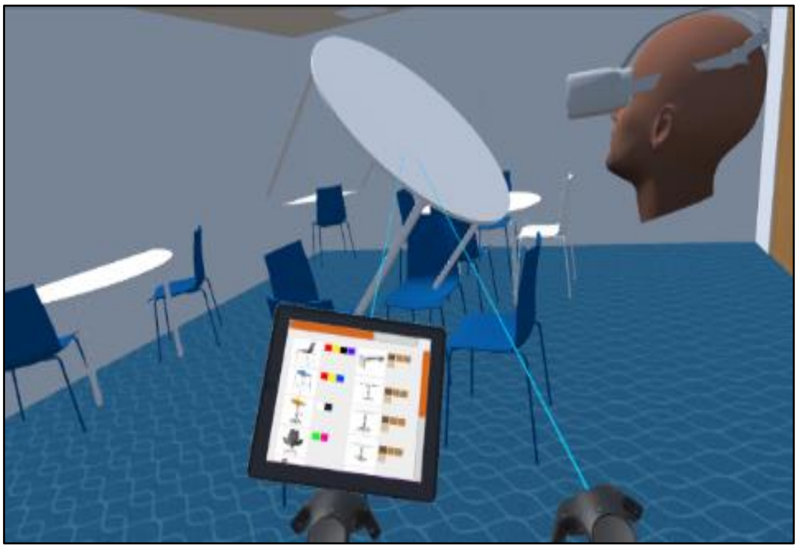

Figure 7.4: Stakeholder interacting with FFE elements

Thus, a novel interactive BIM-based VR application was developed to investigate the effectiveness of the application for FFE's design communication. A sequential exploratory mixed method consisting of a quasi-experiment design and qualitative interview was employed to understand stakeholders' FFE product design choices while using VR-based applications in comparison to 2D-based design (paper-based). A total of twelve FFE stakeholders took part in this study. The experiment focused on measuring users' performance perception and satisfaction while using VR applications and 2D-based methods for design selection. For further details of the development and experiment set up refer to Prabhakaran *et al*. (2021). Figure 7.4 presents the first-person view of a stakeholder interacting with the FFE element to achieve an optimised design.

7.3.4.2. Experiment 2-Distributed VR for FFE's Design Communication and Collaboration

A media-rich immersive VR environment has proven to help FFE's stakeholders understand the design better than the traditional visualization methods (2D based or 3D non-immersive). However, they have not been quite advanced in supporting distributed (multi-user) asynchronous collaboration where stakeholders can interact communicate, and appraise designs collaboratively in real-time and immersive, while at different geographical locations. Additionally, VR user-experience studies suggest that the isolated VR experience delivered by the current application of VR could have a negative impact on task productivity. This experiment posits that this shortcoming of the VR environment could be addressed, allowing concurrent multi-users to interact, communicate and collaborate virtually during design decision-making in the FFE sector. A novel collaborative FFE VE was developed using BIM and a game engine which was then integrated with a Realtime-cloud based client-server architecture for low latency and stable multi-user interaction. Figure 7.5 illustrates the system architecture of the collaborative FFE virtual environment developed for this experiment. The system was tested among (n=26) FFE stakeholders (architects, FFE designers, manufacturer/supplier, contractors, and end-users) to demonstrate usability and functionality. The participants were recruited using the non-probability sampling method (purposive and snowball sampling). Since the VR application used for the experiment is based on a multi-user platform, participants were invited for testing in groups of a minimum of two participants and a maximum of four based on the availability of the number of VR HMDs for trial. The participants were given the freedom to choose from two virtual design scenarios (virtual classroom or virtual science Laboratory).

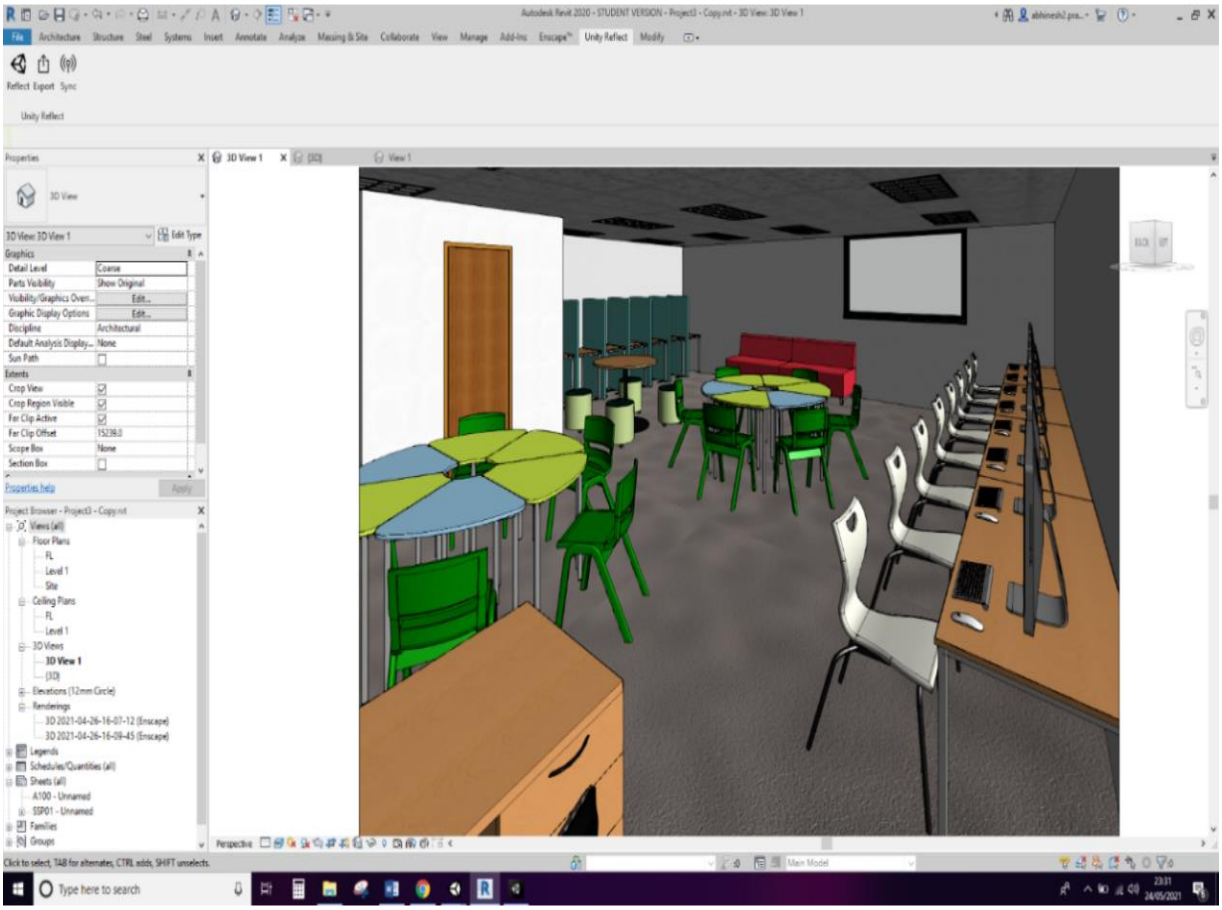

Figure 7.5: System architecture

Even though there was no specific task to be completed, the members of each group were instructed to communicate their design ideas within the group and to finalise a design based on their discussion. Following the trials, a combination of questionnaires using a system usability scale (SUS), sense of presence (ITC-SOPI), and qualitative interviews were employed to elicit the perception of FFE stakeholders in relation to the usability of the developed distributed VR application for FFE's use. Results of the experiment show a high degree of acceptance by stakeholders as a result of improved visualization, multi-user communication, and collaboration in the VE. Figure 7.6 presents the first-person view of one of the stakeholders involved in collaborative decision making, where all stakeholders are represented using avatars.

Figure 7.6: Stakeholders (avatar representation) collaboratively deciding FFE finish (counter-top finish).

7.3.4.3. Systematic Literature Review

A rigorous literature review was carried out to identify the challenges associated with the implementation of VR in the construction sector. For this review, journals published between 2010 and 2019 (inclusive) were selected using inclusion-exclusion criteria. A *four-stage* approach (Figure 7.7), which is built upon the Preferred Reporting Items for Systematic Literature Review and Meta-Analysis (PRISMA) framework (Moher *et al*., 2009) was adopted and the inclusion-exclusion criteria were applied to identify relevant literature for this study.

Below are the inclusion/exclusion criteria, based on which suitable literature was identified:

- Articles published between 2010 and 2021 (inclusive) were considered to maintain currency.
- To maintain a predetermined threshold of quality, only rigorously peer-reviewed journals were considered for this study. Conference papers, book chapters or non-international journals were excluded, thus satisfying the best-evidence principle proposed by Slavin (1986). The non-inclusion of grey literature resulting in publication bias might be considered to be a limitation of this study, but the rationale was solely a trade-off between selecting high-quality literature and the inherent risk of broadening the information bias that must be anticipated when a study of doubtful reliability is included.
- Literature in which theory, concepts or proposals are discussed only, without following any experimental testing or case studies was excluded from this study. The development and implementation process of any Immersive VE is a critical element in identifying the challenges faced when diffusing such developments into architecture and construction workflow. Thus, only literature that was focused on development and validation was considered to be eligible for this study.

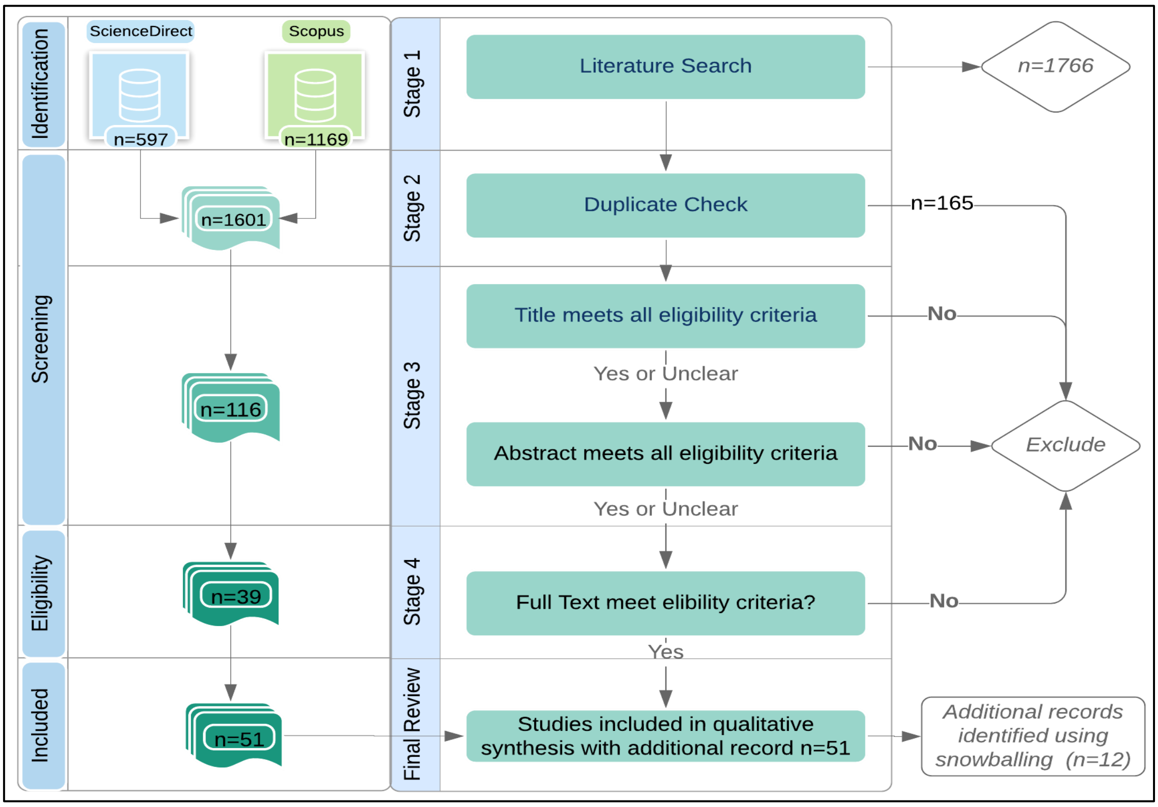

Figure 7.7: Literature selection process

Table 7.2: Benefits facilitating VR implementation

Systematic Literature Review	Label	Reference	Experiment 1	Experiment 2
Improved visualisation/simulation of design.	B1	(Chalhoub and Ayer, 2018; Roupé *et al*., 2016)	√	√
Improved spatial awareness of virtual design//prototype.	B2	(Forbes *et al*., 2018; Hill *et al*., 2019; Lertlakkhanakul *et al*., 2008; Li, 2020)	√	√
Enhanced design communication and coordination.	B3	(Du *et al*., 2018; Yoon *et al*., 2010)	√	√
Improves remote collaboration between stakeholders.	B4	(Du *et al*., 2018; Saeidi *et al*., 2019; Truong *et al*., 2021)		√
Improves our productivity.	B5	(Bahri *et al*., 2019; Berg and Vance, 2017; Bordegoni and Ferrise, 2013)		
Speedy design decision.	B6	(Roupé *et al*., 2016; Zaker and Coloma, 2018)	√	√
Co-presence in remote and virtual collaboration.	B7	(Du *et al*., 2018; Saeidi *et al*., 2019; Truong *et al*., 2021)		√
The ability for multiple users to review design simultaneously in a virtual environment (Multiuser functionality).	B8	(Du *et al*., 2018; Saeidi *et al*., 2019; Truong *et al*., 2021)		√
Enhanced client trust and satisfaction.	B9	(Davila Delgado *et al*., 2020; Roupé *et al*., 2016)		√
Better design option review/ appraisal.	B10	(Du *et al*., 2018; Yoon *et al*., 2010)	√	√
Timesaving.	B11	(Mahamadu *et al*., 2022; Wolfartsberger, 2019; Zaker and Coloma, 2018)	√	
Cost-saving.	B12	(Mahamadu *et al*., 2022; Wolfartsberger, 2019; Zaker and Coloma, 2018)		
Improved understanding of design through immersion compared to traditional methods like paper-based design.	B13	(Chalhoub and Ayer, 2018)	√	
Less cognitive workload when exploring design.	B14	(Jeelani *et al*., 2020; Padilla *et al*., 2018)	√	√
Eliminates the need for physical prototypes.	B15	(Bordegoni and Ferrise, 2013; Freitag *et al*., 2018; Janusz, 2019)	√	√
Improved sensory experience.	B16	(Bahri *et al*., 2019; Jeelani *et al*., 2020)	√	
Improves organisational reputation.	B17	(Davila Delgado *et al*., 2020; Roupé *et al*., 2016; Chalhoub and Ayer, 2018)		
Enables early involvement of technical and non-technical stakeholders.	B18	(Chalhoub and Ayer, 2018; Mahamadu *et al*., 2022)	√	√
Identify design-related issues before they occur.	B19	(Chalhoub and Ayer, 2018; Mahamadu *et al*., 2022; Zaker and Coloma, 2018)	√	

Clients are now demanding better visualisation and digital technology use.	B20	(Davila Delgado *et al*., 2020)	√	
VR is being adopted as part of our BIM implementation mandate.	B21	(Davila Delgado *et al*., 2020)		
Adopting because of ease of integration with BIM.	B22	(Davila Delgado *et al*., 2020)		√
VR has become trendy.	B23	(Zaker and Coloma, 2018)	√	
VR is being used by our peers and competitors.	B24	(Wolfartsberger, 2019)	√	√
The wide availability of VR technologies and devices.	B25	(Moparthi *et al*., 2020)		

Table 7.3: Challenges affecting VR implementation

Systematic Literature Review	Label	Reference	Experiment 1	Experiment 2
Costly Hardware and software	C1	(Chalhoub and Ayer, 2018; Du *et al*., 2018; Mahamadu *et al*., 2022; Perlman *et al*., 2014; Pour Rahimian *et al*., 2019)	√	√
Resistance to adopting the technology.	C2	(Davila Delgado *et al*., 2020)		
Shortage of Skilled Workforce.	C3	(Davila Delgado *et al*., 2020; Mahamadu *et al*., 2022)	√	√
Interoperability between VR development software and construction modelling tools	C4	(Chalhoub and Ayer, 2018; Du *et al*., 2018; El Ammari and Hammad, 2019; Mahamadu *et al*., 2022; Osello *et al*., 2018; Wolfartsberger, 2019)	√	√
Lack of Multi-user functionality.	C5	(Du *et al*., 2018)		√
Require vast dedicated physical space to use VR	C6	(Chalhoub and Ayer, 2018; Du *et al*., 2018; El Ammari and Hammad, 2019; Wolfartsberger, 2019; Zaker and Coloma, 2018)	√	√
Heavy head-mounted devices.	C7	(Oke and Arowoiya, 2021)	√	
Limited view angle in VR display	C8	(Chalhoub and Ayer, 2018; Davila Delgado *et al*., 2020)		
Poor resolution of VR display.	C9	(Davila Delgado *et al*., 2020; Yan *et al*., 2018; Yuan *et al*., 2018)		
Challenges associated with restricted user mobility.	C10	(Davila Delgado *et al*., 2020; Du *et al*., 2018; Mahamadu *et al*., 2022)	√	
Difficulties in achieving a high frame rate (smoother virtual scenes).	C11	(Mahamadu *et al*., 2022; Roupé *et al*., 2016)	√	√
Portability of VR hardware (such as long cables, VR movement trackers which need to be installed on a tripod, high specification laptops/PC which are heavy).	C12	(El Ammari and Hammad, 2019; Mahamadu *et al*., 2022)	√	
Difficulties associated with replication of real-world environment (realism of the virtual content).	C13	(Cao *et al*., 2019; Zhang *et al*., 2019)		√
Accuracy of the model in compression to as modelled in construction modelling tool vs as projected in a virtual environment.	C14	(Heydarian and Golparvar-Fard, 2011; Portman *et al*., 2015; Zhang *et al*., 2019)		
Ethical issues such as user privacy, data protection etc.	C15	(El Ammari and Hammad, 2019; Portman *et al*., 2015)		
Challenges associated with lack of sensory modalities such as sense of touch, and smell in VR when compared to physical mock-ups.	C16	(Osello *et al*., 2018; Portman *et al*., 2015; Shi *et al*., 2020)		
Health and Safety Issues such as tripping, collision, and eye strain.	C17	(Mahamadu *et al*., 2022; Pour Rahimian *et al*., 2019; Sacks *et al*., 2013)	√	

Systematic Literature Review	Label	Reference	Experiment 1	Experiment 2
Negative effects such as dizziness, and nausea when using VR.	C18	(Klerk *et al*., 2019; Mahamadu *et al*., 2022; Pour Rahimian *et al*., 2019; Sacks *et al*., 2013)	√	√
Limitations of tether-free head-mounted displays such as in the ability to process high-quality virtual environment, power and battery limitations, etc.	C19	(Du *et al*., 2018; El Ammari and Hammad, 2019; Wolfartsberger, 2019; Zaker and Coloma, 2018)		√
Lack of client's interest in VR.	C20	(Davila Delgado *et al*., 2020)		
Lack of business case/Return on Investment.	C21	(Davila Delgado *et al*., 2020)		
Steep learning curve.	C22	(Sacks *et al*., 2013)		√
Challenges associated with the virtual environment 3D content creation.	C23	(Cao *et al*., 2019; Chalhoub and Ayer, 2018; Mahamadu *et al*., 2022; Pour Rahimian *et al*., 2019)		
Lack of institutional drivers.	C24	(Davila Delgado *et al*., 2020)		
Challenges associated with the development of custom programmes/scripts to enable VR interaction.	C25	(Du *et al*., 2018; El Ammari and Hammad, 2019; Pour Rahimian *et al*., 2019; Sacks *et al*., 2013; Shi *et al*., 2020; Zhang *et al*., 2019)	√	√
Lack of understanding of benefits of the VR technology.	C26	(Davila Delgado *et al*., 2020)		
Lack of funding for R and D.	C27	(Davila Delgado *et al*., 2020)		
Network Latency issues (Delays between action and reaction in the VR environment due to low-speed internet connectivity, heavy model size etc.).	C28	(Du *et al*., 2018)		√
Higher processing requirement.	C29	(Mahamadu *et al*., 2022)		√
Isolated VR experience (Single user VR experience can be isolating to the person using the VR headset).	C30		√	√
Expensive Training.	C31	(Davila Delgado *et al*., 2020)		
Clunky user interface.	C32	(Davila Delgado *et al*., 2020)	√	√

Out of 1766 journals identified from top construction journal databases (Scopus and Science Direct), 51 eligible journals were finally chosen for review. For further details refer to Prabhakaran *et al.* (2022).

7.4. Results and Discussion

7.4.1. Background of Respondents

As presented in Table 7.1, 35.90% of respondents were architects, 20.51% were BIM coordinators, 18.80% were interior designers, 17.90% were FFE designers and 6.80% were FFE consultants who specialised in the design and fit-out of FFE elements. Thus, the samples represent a heterogeneous group of FFE stakeholders who played a vital role in the planning and designing of FFE arrangements during the design of a facility. Also, 65.80 % of the respondents were male and 34.20% were females. The majority of the participants (62.40%) had previous experience in using VR-based applications.

7.4.2. Characteristics of Respondents' Organisations

The characteristics of the respondents' organisation (Table 7.4) were also assessed in Section (1) of the questionnaire. This assessment showed that 57.30% of the respondents represented architectural firms, followed by 22.2% that were focused on construction project management, 12.8% were FFE suppliers and 7.70% were FFE contractors. Within this composition, 38.5% of the firms were consultancies, 25.6% were Tier 2 contractors, 19.7% and 16.20% were Tier 1 and 3 respectively. Also, the number of employees in most of the firms (35%) was between 1 and 9, followed by 17.10% which had more than 250 employees.

The participants were asked also to indicate the type of projects that their organisation undertook. The majority of the organisations (65%) focused on construction activities of residential buildings, followed by 57.33% that focused on commercial building developments and 32.76% that focused on educational institutions.

Table 7.4: Respondent's organisational characteristic

		Frequency	Percentage	Cumulative
Type of Firm	Architectural	67	57.3	57.3
	Project Management	26	22.2	79.5
	FFE Contractor	9	7.7	87.2
	FFE Supplier	15	12.8	100
Firm Level	Consultancy	45	38.5	38.5
	Tier 1	23	19.7	58.1
	Tier 2	30	25.6	83.8
	Tier 3	19	16.20	100
Firm Size	1-9 Employees	41	35.0	35.0
	10-49 Employees	33	28.20	63.2
	50-149 Employees	21	17.90	81.20
	150-250 Employees	2	1.7	82.90
	>250 Employees	20	17.10	100
Firm's General Experience	0-4 Years	28	23.9	23.9
	5-10 Years	38	32.5	56.4
	11-16 Years	23	19.7	76.1
	17-22 Years	4	3.40	79.5
	>23 Years	24	20.50	100

Figure 7.8 shows further details about the frequency of types of construction undertaken by the respondents' organisations across various projects. Participants were asked further, about the extent to which they used various methods to communicate designs (Figure 7.9) such as 2D paper-based, 2D digital, 3D BIM etc. while selecting furniture and interior fixtures for the types of projects they undertook. Across all the four different types of projects that participants' organisations undertook (health care, educational, commercial and residential) 2D paper-based was the most extensively used method of design communication in the FFE sector. This finding

reiterates the findings of Prabhakaran *et al*. (2021) who noted that the adoption of technology was low in the FFE sector that relied mostly on 2D methods such as sketches, catalogues etc. to communicate designs resulting in poor productivity. Also, 2D digital methods (e.g., 2D plans on screen-based interfaces) and 3D BIM models were the second and third most-used mediums for design communication. Recently, the adoption of data-rich, digital models to communicate furniture designs using BIM has been embraced in the FFE sector. However, their utilisation across different types of projects is not evenly distributed. For instance, as shown in Figure 7.9, it is evident that BIM for FFE design was used the least in healthcare projects, which confirms the findings of Mahamadu *et al*. (2022).

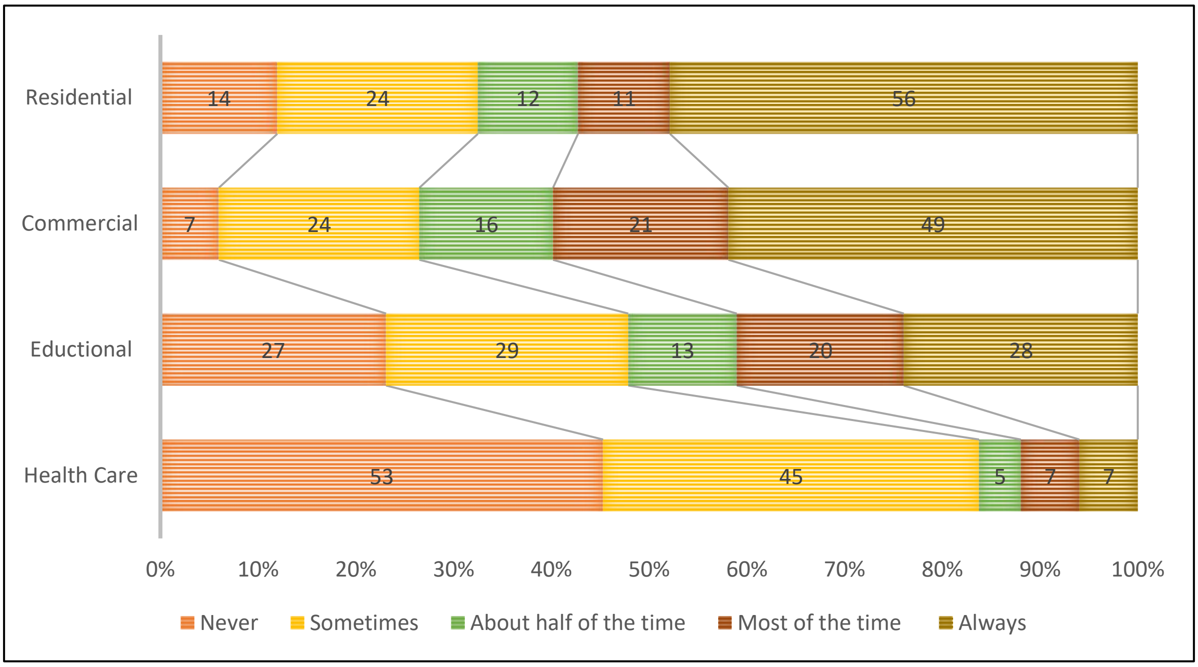

Figure 7.8: Type of projects respondents' organisation undertake

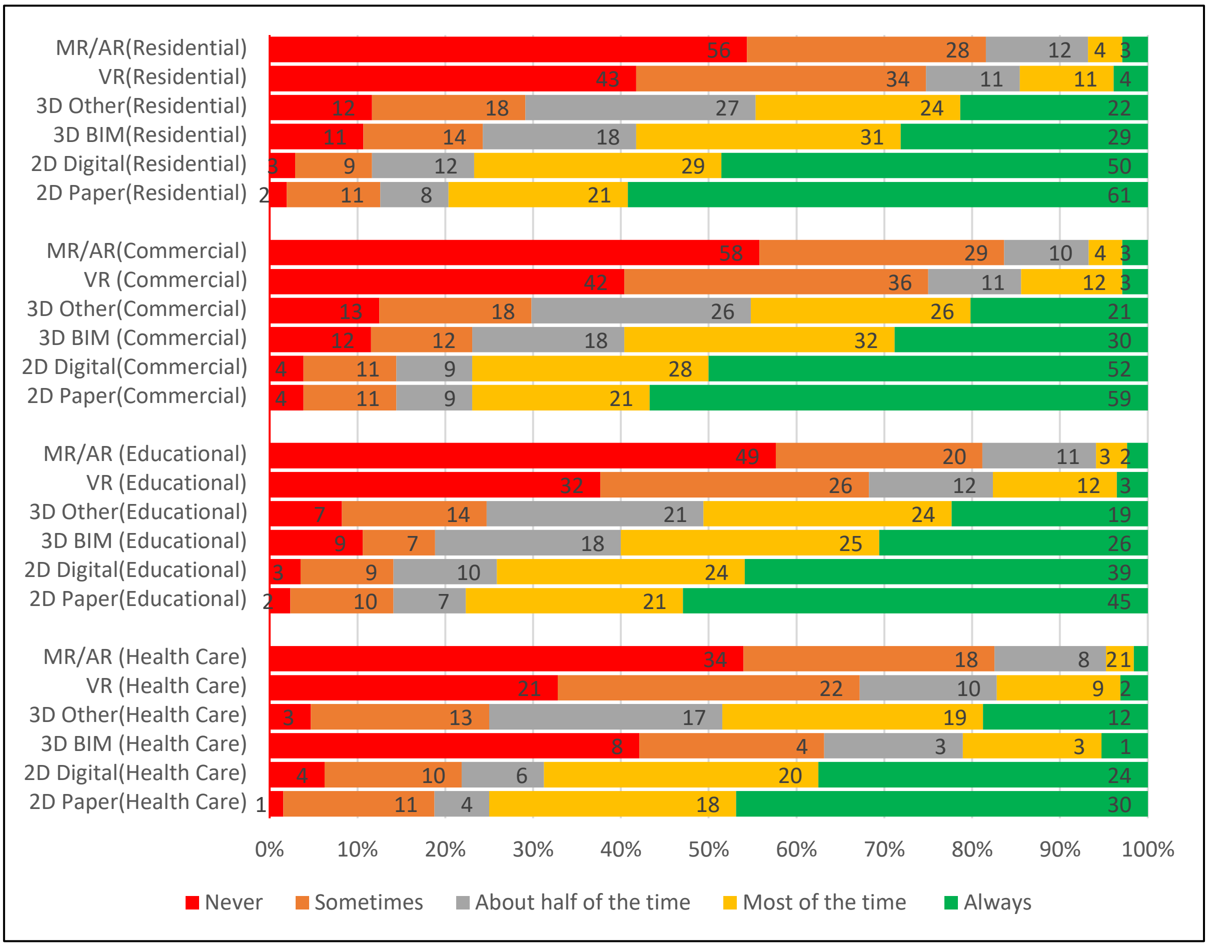

Figure 7.9: Design communication methods used in different projects

It is noted also that extended reality technologies (VR, MR and AR) were the least used method to communicate designs during the selection of furniture and interior fit-outs in projects. This could be attributed to various challenges such as cost and skill requirements.

7.4.3. Usefulness and Intention to Adopt VR-based Application to Communicate and Coordinate FFE Design

The questionnaire included video demonstrations of the two VR applications (single-user VR and distributed VR for FFE design communication and coordination, explained in detail under Experiment 1 and Experiment 2 above. The participants were asked to rate the usefulness of these applications for design communication and coordination during the projects on which they worked (Table 7.5). The majority of the participants (57.26%) considered both the applications to be extremely useful, 35.04% and 31.62% of respondents considered distributed and single-user VR to be very useful, respectively for communicating and collaborating about FFE design. Figure 7.10 illustrates the respondents' perceptions about the usefulness of both VR applications for FFE's design communication and collaboration.

Participants were asked to indicate their intention to adopt and invest in similar VR-based applications for design communication and coordination. The responses indicating the intention to adopt were grouped into three categories (Table 7.5): a) Non-Adopter (NA), b) Medium-Adopter (MA) and c) High-Adopter (HA). The majority of the respondents (50.4 %) had a high intention to adopt VR technology, 43.6% were low adopters, and 6.0% of respondents had no intention to adopt VR technology.

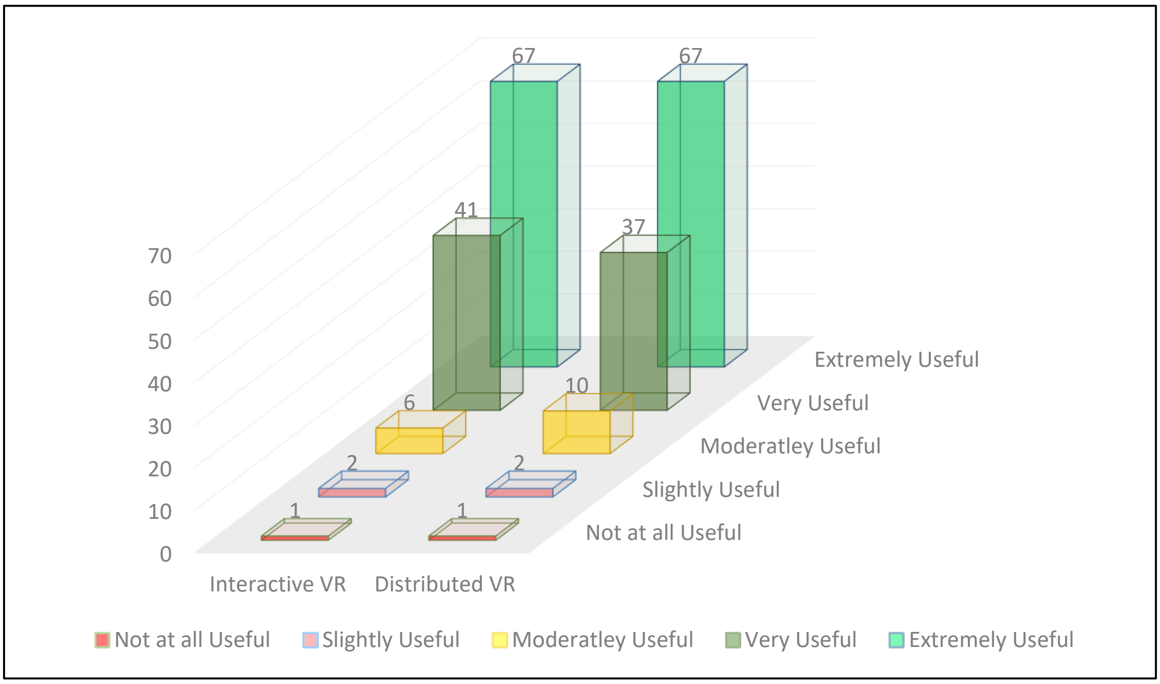

Figure 7.10: Usefulness of interactive VR and distributed VR application in the FFE sector

A Spearman's rho correlation analysis was conducted to assess the relationship between the respondents' intention to adopt and their intention to invest in VR-based technology. There was no significant correlation identified between the two (r_s = 0.095, p =0.306).

A Kruskal-Wallis ANOVA test was conducted as well to determine if there were significant differences in a) the usefulness scores of the two VR-based applications demonstrated (single-user and distributed VR) for use in the FFE sector, b) the respondents' role, c) their intention to invest in VR-based applications and d) their intention to adopt VR technology. There were no statistically significant differences identified between the role of the respondents and their level of intention to adopt VR technology. Furthermore, the distributions of the usefulness scores for single-user and distributed VR applications as well as scores for intention to invest in VR technology were not similar for all groups, based on visual inspection of the box plot. Distributions of the scores for the usefulness of the single-user VR application, χ^2 (2) =13.171, p = 0.001, and scores for the usefulness of the distributed VR application, χ^2 (2) = 19.889, p = 0.001, were significantly different statistically between the different levels of adopters (NA, MA, and HA). Subsequently, a pair-wise comparison (Table 7.6) was performed using Dunn's procedure (1964) with a Bonferroni correction for multiple comparisons.

Table 7. 5: Intention to adopt and spend on VR based technology

Intention to Adopt and Spend on VR		Frequency	Percentage	Cumulative
Intention to Adopt VR	Non-Adopter	7	6.0	6.0
	Medium-Adopter	51	43.6	49.6
	High Adopter	59	50.4	100
Intention to Spend	Nothing	8	6.8	6.8
	£1-500	43	36.8	43.6
	£500-3000	42	35.9	79.5
	£3000-10000	16	13.7	93.2
	<£10000	8	6.8	100
Usefulness of VR applications Demonstrated				
Interactive VR	Extremely Useful	67	57.3	100
	Very useful	41	35.0	42.7
	Moderately Useful	6	5.1	7.7
	Slightly Useful	2	1.7	2.6
	Not at all Useful	1	0.9	0.9
Distributed VR	Extremely Useful	67	57.3	100
	Very useful	37	31.6	42.7
	Moderately Useful	10	8.5	11.1
	Slightly Useful	2	1.7	2.60
	Not at all Useful	1	0.9	0.9

In the case of the single-user VR application, this *post hoc* analysis revealed a statistically significant difference in the usefulness scores between NA (mean rank = 37.93) and HA (mean rank = 68.44, p=0.031) and HA and MA (mean rank = 50.97, p= 0.006) groups but not between the NA and MA (p = 0.830) groups suggesting that the HA group considered the single-user VR application, extremely useful when compared to the MA and NA groups. For the distributed VR application, the post hoc analysis revealed a statistically significant difference in the usefulness scores between NA (mean rank = 21.57) and MA (mean rank = 52.55, p = 0.031) groups, the NA and HA (mean rank = 69.02, p = 0.001) groups and the MA and HA (p = 0.012) groups suggesting that the HA group considered distributed VR application to be extremely useful.

Table 7.6: Pairwise comparison

	Levels of Adoption Mean/Median Rank	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.[a]
Interactive VR	Non-Adopter$^{37.93}$-Medium Adopter$^{50.97}$	-13.042	11.990	-1.088	0.277	0.830
	Non-Adopter$^{37.93}$-High Adopter$^{68.44}$	-30.512	11.891	-2.566	0.010	0.031
	Medium Adopter$^{50.97}$-High Adopter$^{68.44}$	-17.470	5.687	-3.072	0.002	0.006
Distributed VR	Non-Adopter$^{21.57}$-Medium Adopter$^{52.55}$	-30.978	12.075	-2.566	.010	0.031
	Non-Adopter$^{21.57}$-High Adopter$^{69.02}$	-47.446	11.975	-3.962	<0.001	0.001
	Medium Adopter$^{52.55}$-High Adopter$^{69.02}$	-16.468	5.728	-2.875	0.004	0.012
Intention to Spend	Non-Adopter$^{15.43}$-Medium Adopter$^{64.30}$	-48.875	12.997	-3.766	<0.001	0.001
	Non-Adopter$^{15.43}$-High Adopter$^{59.58}$	-44.156	12.870	-3.431	<0.001	0.002
	Medium Adopter$^{64.30}$-High Adopter$^{59.58}$	4.719	6.156	0.767	0.443	1.00
Immature Technolog	Non-Adopter$^{2.33}$-Medium Adopter$^{3.25}$	-26.290	13.659	-1.925	0.054	0.163
	Non-Adopter$^{2.33}$-High Adopter$^{3.66}$	-40.024	13.546	-2.955	0.003	0.009
	Medium Adopter$^{3.25}$-High Adopter$^{3.66}$	-13.734	6.479	-2.120	0.034	0.045
Perceived Cost	Non-Adopter$^{3.80}$-Medium Adopter$^{3.80}$	-11.445	13.607	-0.841	0.400	1.00
	Non-Adopter$^{3.80}$-High Adopter$^{4.20}$	-26.510	13.495	-1.964	0.049	0.148
	Medium Adopter$^{3.80}$-High Adopter$^{4.20}$	-15.064	6.454	-2.334	0.020	0.046
Skill Shortage	Non-Adopter$^{3.00}$-Medium Adopter$^{3.50}$	-23.782	13.641	-1.743	0.081	0.244
	Non-Adopter$^{3.00}$-High Adopter$^{4.00}$	-36.810	13.529	-2.721	0.007	0.020
	Medium Adopter$^{3.50}$-High Adopter$^{4.00}$	-13.028	6.471	-2.013	0.044	0.132

Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests
b. Significance values highlighted

Further analysis using cross-tabulation revealed that most of the respondents in the *HA* category were architects (n = 22) and interior designers (n = 19), suggesting that architects and interior designers had the highest intention to adopt VR technology and also considered both VR applications to be extremely useful for design communication and coordination. This could be attributed to the fact that, unlike FFE designers and consultants, for architects and interior designers, the utilisation of similar VR applications for design communication and coordination belongs to a wider spectrum such as lighting simulation (Hegazy *et al.*, 2021), preoccupancy evaluation (Tseng and Giau, 2021), spatial interaction management

(Lertlakkhanakul *et al*., 2008), virtual prototyping (Li *et al*., 2012), and rapid conceptual design (Klerk *et al*., 2019).

Furthermore, the distributions of intention to invest in VR technology scores were not similar for all groups, based on visual inspection of the box plot. Distributions of the scores for intention to invest in VR technology were significantly different statistically between the different levels of intention to adopt VR technology, $\chi^2(2) = 14.224$, $p = 0.001$. The result of a pairwise comparison (Table 7.6) using Dunn's procedure (1964) with a Bonferroni correction for multiple comparisons revealed statistically significant differences in the score for intention to invest in VR technology between NA (mean rank = 15.43) and HA (mean rank = 59.58, p = 0.001) groups, and NA and MA (mean rank = 64.58, p = 0.002) groups, but not between the MA and HA (p = 0.930) groups, suggesting that the MA group, of which were the majority were architects (n =18) and FFE designers (n = 13) had the highest intention to spend on VR based technology.

7.4.4. Factors Affecting and Facilitating VR Implementation in FFE Sector

7.4.4.1. Reliability Analysis

To test the internal consistency of the factors investigated in section (2) of the questionnaire, a reliability analysis was conducted using Cronbach's alpha (CA). The threshold CA value which determines the internal consistency is 0.70 or higher (Hair, 2009). The Cronbach's alpha for the challenges that affect the implementation of VR in the FFE sector was 0.92 and for the benefits that facilitate the implementation of VR in the FFE sector was 0.90 which confirms a higher internal consistency of the factors used in the questionnaire. Subsequently, the implementation factors were categorised into components (detailed in sub-section 4.4.2) and their internal consistency was measured. The results (Table 7.7) indicated that all the components had a CA value higher than 0.70 indicating a high internal consistency.

7.4.4.2. Ranking and Categorisation of VR Implementation Factors

The VR implementation factors identified were examined using descriptive statistics (Tables 7.7 and 7.8) to identify the central tendency. This allowed further ranking of the factors based on the responses of the participants on how each factor affects/facilitates VR implementation in their organisation. Tables 7.7 and 7.8 show the ranking of each factor based on its mean score. To simplify the complexity of a large number of data sets each of the VR implementation factors was categorised into components (Tables 7.7 and 7.8). These components were also ranked based on their mean scores. In the next sub-section, the dynamics and correlation of each of these components with the participants' intention to adopt VR technology have been examined in detail.

7.4.4.3. Dynamics between VR Implementation Components and Intention to adopt VR Technology

7.4.4.3.1. Challenges affecting VR Implementation in the FFE Sector

Based on the respondents' perceptions (Table 7.7), *perceived cost* was ranked as the topmost challenge that could affect the implementation of VR technology in the FFE sector. In the *perceived cost* components, respondents considered procurement of hardware such as VR devices, high-performance laptops etc. and software such as VE development game engines and other supporting software to be the most challenging factor. Based on studies such as those carried out by Davila Delgado *et al*. (2020) costs have also been reported as a major constraint on the implementation of VR. While the cost of a head-mounted display (HMD) has decreased because of the recent advancements in technology, the costs associated with the supporting software, such as game engines, modelling tools etc., and hardware such as high-performance computer, as well as the cost of training/ hiring a skilled workforce are considered as a major challenge in the adoption of VR technology in the FFE sector. To examine whether any causal relationship existed between the *perceived cost* and respondents' intentions to adopt virtual reality technology for design communication and coordination, Spearman's correlation analysis was carried out. A significant negative correlation (r_s = -0.256, p =0.005) was identified, suggesting that the higher the *perceived cost,* the lower the intention to adopt VR technology. These findings confirmed the findings from the systematic literature review and the two experiments carried out.

A Kruskal-Wallis ANOVA test was conducted also to determine if there were differences in the scores of *perceived cost* between the groups (NA, MA and HA) that differed from their levels of intention to adopt VR technology. Distributions of all of the scores for the components were similar for all groups, based on visual inspection of the box plot. The median scores of *perceived cost*, $\chi^2(2) = 9.494$, p = 0.022 were significantly different statistically between the different levels of intention to adopt VR technology. Subsequently, pair-wise comparisons (Table 7.6) were performed using Dunn's procedure (1964) with a Bonferroni correction for multiple comparisons. The *post hoc* analysis revealed statistically significant differences in median scores for MA (3.80) and HA (4.20) (p =0.046) group but not between NA (3.80) and HA group as well as NA and MA groups, suggesting that the HA group, followed by MA group considered *perceived cost* as the most critical challenge.

The respondents ranked *skill shortage* as the second most critical challenge that could affect the adoption of VR in the FFE sector. A Spearman's correlation analysis was carried out to examine the causal relationship between *Skill Shortage* and the respondents' intention to adopt

VR technology. A significantly negative correlation (r_s = -0.266, p =0.004) was identified. This finding confirmed the arguments of Allen, (2019), who noted that the AEC industry as whole faces massive skill shortages which is hampering the adoption of VR technology.

Table 7.7: Ranking and categorisation of challenges

Components	α	Component Rank	Label	Factors	Mean	Median	SD	Factor Rank
Perceived Cost	0.73	1	C1	Costly Hardware and software	4.34	5	0.99	1
			C32	Expensive Training.	4.08	4	1.17	2
			C28	Lack of funding for R and D.	4	4	1.14	3
			C21	Lack of business case/Return on Investment.	3.5	4	1.22	4
			C6	Require vast dedicated physical space to use VR	3.31	3	1.17	5
Skill Shortage	0.85	2	C23	Steep learning curve.	3.98	4	1.13	1
			C24	Challenges associated with the virtual environment 3D content creation	3.82	4	1.09	2
			C26	Challenges associated with the development of custom programmes/scripts to enable VR interaction.	3.79	4	1.02	3
			C3	Shortage of Skilled Workforce.	3.74	4	1.23	4
			C11	Difficulties in achieving a high frame rate (smoother virtual scenes).	3.74	4	1.23	5
			C14	Accuracy of the model in compression to as modelled in construction modelling tool vs as projected in a virtual environment.	3.66	4	1.09	6
			C13	Difficulties associated with replication of real-world environment (realism of the virtual content).	3.63	4	1.15	7
			C33	Clunky user interface.	2.78	3	1.14	8
Immature Technology	0.82	3	C30	Higher processing requirement.	4.13	4	1.03	1
			C4	Interoperability between VR development software and construction modelling tools	3.87	4	1.13	2
			C31	Isolated VR experience (Single user VR experience can be isolating to the person using the VR headset).	3.86	4	1.15	3
			C12	Portability of VR hardware (such as long cables, VR movement trackers which need to be installed on a tripod, high specification laptops/PC which are heavy).	3.61	4	1.12	4
			C29	Network Latency issues (Delays between action and reaction in the VR environment due to low-speed internet connectivity, heavy model size etc.).	3.59	4	1.19	5
			C19	Limitations of tether-free head-mounted displays such as in the ability to process high-quality virtual environment, power and battery limitations, etc.	3.56	4	1.17	6
			C5	Lack of Multi-user functionality.	3.55	4	1.03	7
			C10	Challenges associated with restricted user mobility.	3.34	3	1.23	8
			C16	Challenges associated with lack of sensory modalities such as sense of touch, and smell in VR when compared to physical mock-ups.	3.33	4	1.22	9

			C9	Poor resolution of VR display.	2.79	3	1.3	10
			C7	Heavy head-mounted devices.	2.74	3	1.27	11
			C8	Limited view angle in VR display	2.68	2	1.31	12
Lack of Champions and Drivers	0.72	4	C25	Lack of institutional drivers.	3.66	4	1.08	1
			C27	Lack of understanding of benefits of the VR technology.	3.5	4	1.19	2
			C20	Lack of client's interest in VR.	3.37	3	1.28	3
			C2	Resistance to adopting the technology.	2.82	3	1.33	4
Privacy and Safety	0.71	5	C18	Negative effects such as dizziness, and nausea when using VR.	3.56	4	1.17	1
			C17	Health and Safety Issues such as tripping, collision, and eye strain.	3.01	3	1.25	2
			C15	Ethical issues such as user privacy, data protection etc.	2.96	3	1.35	3

In the report by Innovate UK (2019), titled: *The immersive economy in the UK*, it was suggested that *skill shortage* was one of the biggest challenges faced by industries in adopting VR. The results of a survey by Mateos-Garcia *et al*. (2019) revealed that 65% of the industries considered *skill shortage* as a major challenge. Previous studies like Prabhakaran *et al.* (2022) have also reported *skill shortage* as a major challenge faced by the AEC industry. Since the FFE sector is a low-profit margin sector, this challenge could pose the same threat as *perceived cost*, because additional training to upskill the workforce can severely impact the profit.

A Kruskal-Wallis ANOVA test was conducted to determine if there were any differences in the scores for *skill shortage* between the groups (NA, MA and HA) that differed from their levels of intention to adopt VR technology. The median scores for *skill shortage* ($\chi^2(2) = 9.494$, $p = 0.009$) were significantly different statistically between the different levels of intention to adopt VR technology. Subsequently, pair-wise comparisons (Table 7.6) were performed using Dunn's procedure (1964) with a Bonferroni correction for multiple comparisons. The *post hoc* analysis revealed statistically significant differences in the median scores of NA (3.00) and HA (4.00) ($p = 0.020$) groups but not between other groups suggesting that the HA group considers the *skill shortage* as the most critical challenge followed by the MA groups.

A technology is considered to be immature when there are flaws that prevent the users from reaping the full benefit of using that technology (Banke, 2017). Based on the respondents' perception, the *immature technology* component was ranked as the third critical challenge that can affect the implementation of VR based technology in the FFE sector. A significant, negative correlation (r_s = -0.284, p =0.002) between intention to adopt VR technology and *immature technology* was identified suggesting that technological immaturity adversely affects the FFE sector's intention to adopt VR technology. One of the major technological challenges that limit the adoption of VR in the construction sector is the high processing requirement which leads to the additional cost and portability issues of VR devices (Du *et al*., 2018). Similarly, interoperability issues were another major technological challenge that VR developers in the AEC industry face. Studies like (Chalhoub and Ayer, 2018; Du *et al*., 2018) have also reported the iteration requirements before the VE is VR ready. These challenges also add up to the additional cost required for the middleware software for the iterations. A Kruskal-Wallis ANOVA test was carried out to identify the difference in the scores for *immature technology* between the groups (NA, MA and HA) that differed in their levels of intention to adopt VR technology. The median scores of *Immature Technology* ($\chi^2(2) = 10.986$, p = 0.004) were significantly different statistically between the different levels of intention to adopt VR technology. The pair-wise comparison using Dunn's procedure (1964) with a Bonferroni correction for multiple comparisons revealed that HA (3.66) (p = 0.009) group considers *immature technology* as a critical challenge when compared to MA and NA groups. *Lack of drivers* and *privacy and safety* were the fourth and fifth challenges that respondents considered to be critical. Spearman's correlation analysis revealed no significant relationship with the respondent's intention to adopt VR technology suggesting that the *Lack of drivers* and *Privacy and safety* has no impact on VR implementation in the FFE sector.

7.4.4.3.2. Benefits Facilitating VR Implementation in FFE Sector

Respondents considered *improved design communication* to be the topmost benefit (Table 7.8) that can facilitate VR Implementation in their organisations followed by, *enhanced user experience*, *facilitating conditions* and *productivity and efficiency*. However, Spearman's correlation analysis revealed a positive correlation (r_s = 0.185, p =0.0045) only between *productivity and efficacy* and respondents' intention to adopt VR technology. This indicated that even though respondents considered all the other components to be highly important, only *productivity and efficiency* drive the intention to adopt VR technology in the FFE sector. The British Furniture Confederation, (2018) reported that being a low technology adoption industry has resulted in a drastic decline in productivity of the FFE sector. Similarly, reports by Barbosa *et al*., (2017) also highlighted the productivity and performance decline in the FFE sector, attributing it to the lack of innovation and adoption of digital processes such as BIM (NBS, 2010) and immersive technology (Garcia, 2017). Also in the industrial Review of TEM, the low adoption rate of digitalization in the UK's FFE sector was emphasised, which was thus facing low productivity and high international competition in its internal market. At the same time, the report highlights the fact that the FFE sector could benefit from a rapid increase in its competitiveness through digitalization. Johnson *et al*. (2010) suggested that any sector of the construction industry should strive to innovate in order to meet the cultural challenge of collaboration and global competition to yield productivity. These reports indicate the necessity for the FFE sector to undergo a drastic amelioration in its current utilisation of technologies to overcome the prevailing inefficiency. This realisation of the need for improvements in productivity and efficiency using VR could have influenced the respondents' intention to adopt VR technology. However, it is worth noting that even though the other three benefits components did not reveal any significant correlation with respondents' intention to adopt VR technology, these components also had an influence in determining *productivity and efficiency*. Spearman's correlation analysis confirms a strong positive correlation with *productivity and efficiency* and other three components; *enhanced user experience* (r_s = 0.571, p =0.001), *improved design communication* (r_s = 0.519, p =0.001) and *facilitating condition* (r_s = 0.403, p = 0.001). This is also in line with findings of experiments one and two as well as other studies (Chalhoub and Ayer, 2018; Du *et al*., 2018; Yoon *et al.*, 2010) which suggest that the utilisation of VR in the FFE sector can improve the design communication through delivering enhanced user experience like improved visualisation, spatial awareness and co-presence offered by distributed VR.

Table 7.8: Ranking and categorisation of benefits

Components	α	Rank	Label	Factors	Mean	Median	SD	Rank
Improved Design Communication	0.78	1	B10	Better design option review/ appraisal.	4.27	4	0.8	1
			B19	Identify design-related issues before they occur.	4.14	4	0.84	2
			B18	Enables early involvement of technical and non-technical stakeholders.	4.09	4	0.85	3
			B3	Enhanced design communication and coordination.	4.05	4	0.95	4
			B8	The ability for multiple users to review design simultaneously in a virtual environment (Multiuser functionality).	4.03	4	0.9	5
			B4	Improves remote collaboration between stakeholders.	4.02	4	0.95	6
Enhanced User Experience	0.71	2	B1	Improved visualisation/simulation of design.	4.46	5	0.82	1
			B13	Improved understanding of design through immersion compared to traditional methods like paper-based design.	4.05	4	0.95	2
			B14	Less cognitive workload when exploring design.	3.95	4	0.9	3
			B2	Improved spatial awareness of virtual design//prototype.	3.91	4	0.92	4
			B16	Improved sensory experience.	3.88	4	0.92	5
			B7	Co-presence in remote and virtual collaboration.	3.87	4	0.96	6
Facilitating Conditions	0.73	3	B9	Enhanced client trust and satisfaction.	4.21	4	0.76	1
			B23	VR has become trendy.	4.03	4	0.91	2
			B17	Improves organisational reputation.	3.99	4	0.85	3
			B20	Clients are now demanding better visualisation and digital technology use.	3.99	4	0.96	4
			B24	VR is being used by our peers and competitors.	3.9	4	1.09	5
			B25	The wide availability of VR technologies and devices.	3.85	4	1.17	6
			B21	VR is being adopted as part of our BIM implementation mandate.	3.79	4	1.04	7
			B22	Adopting because of ease of integration with BIM.	3.69	4	1.11	8
Productivity and Efficiency	0.75	4	B15	Eliminates the need for physical prototypes.	3.97	4	1.01	1
			B6	Speedy design decision.	3.97	4	0.96	2
			B11	Timesaving.	3.93	4	1.01	3
			B5	Improves our productivity.	3.85	4	0.94	4
			B12	Cost-saving.	3.84	4	1.08	5

7.5. Conclusion

This study presented as a mixed research study of the factors that affect/facilitate the utility and adoption of two VR applications in the FFE sector. To achieve these objectives, the factors which affect/facilitate VR adoption in the FFE sector were identified using two experiments that were carried out among FFE stakeholders, along with a detailed systematic literature review. To solicit the opinion of the FFE stakeholders about the two VR applications developed for the experiments and the factors identified, a survey questionnaire was administered to n = 117 FFE stakeholders. Results indicate that majority of respondents considered the single-user and multi-user VR applications to be extremely useful for the FFE sector. The Kruskal-Wallis ANOVA test revealed that architects and interior designers who had a higher intention to adopt VR technology, considered both VR applications to be extremely useful compared with medium adopters and non-adopters. The VR implementation factors were categorised into components and were ranked based on their mean. A total of five categories of challenges and four categories of benefits were identified. To determine the relationship of these components with the intention of FFE stakeholders to adopt VR technology, a Kruskal-Wallis ANOVA test and Spearman's correlation analysis were carried out. Spearman's correlation analysis revealed that perceived cost, skill shortage and immature technology could significantly affect the respondent's intention to adopt VR technology. The Kruskal-Wallis ANOVA test revealed that respondents with a higher intention to adopt VR technology considered perceived cost, skill shortage and immature technology as highly critical for VR adoption in their organisation. In terms of benefits that facilitate VR adoption in the FFE sector Kruskal-Wallis ANOVA test revealed no significant differences between the component's score and the respondent's intention to adopt VR technology. However, Spearman's correlation revealed that productivity and efficiency achieved through the utilisation of VR could drive the adoption of VR in the FFE sector. This study contributes to the body of knowledge by identifying and categorising the myriad of factors that affect/facilitate the adoption of VR in the FFE sector as well as by probing into the dynamics of how various antecedent conditions are related to determining the intention to adopt VR-based tools for communicating and co-ordinating design in the FFE Sectors.

The findings and insights provided in this study can be most useful for the AEC industry and specifically the FFE sector which is in the process of digitalisation. This study provides the practitioners with a valuable indication of which factors to consider devising mitigation plans for streamlined VR adoption. Also, with the introduction of VR-based collaborative environments such as Metaverse, the transition to immersive collaboration will be easier. However, some of the existing limitations like interoperability between BIM authoring tools and VE development packages need to be considered and more studies are required to explore the possibilities of utilising Metaverse as a design communication and coordination tool. It is worth noting that the distributed VR developed for Experiment 2 of this study appears to share close functional similarities with Metaverse, however, more studies are required in this area to understand whether these two applications share common limitations and to develop ways to alleviate any limitations for a smoother adoption of these technologies.

Chapter 8: Discussion

8.1. Introduction

In this Chapter, the findings from the development, testing and validation of the interactive and distributed VR applications (Chapters 4, 5, 6 and 7) are reflected in the context of the literature, theory and previous studies (Chapters 2 and 3). The discussion includes a deeper exploration of the findings from the development, testing and validation of the interactive and distributed VR applications through a critical synthesis of various segments of the results as well as a comparison with the findings of the literature reviewed and state-of-the-art VR applications used in the FFE sector. This helps to clarify the understanding of the research problem and how it has been addressed by the findings.

8.2. Overview

When integrated with the workflow of FFE design, VR applications assist stakeholders to experience the spaces before they are constructed physically and use the experience as a spatial coordination tool (Good and Tan, 1994; Wang and Wang, 2008). The visual information that is conveyed through virtual representation is beneficial for the FFE sector because client procurement decisions are affected by information about colour, patterns, visual texture, ergonomics and materials (Yoon *et al*., 2010). However, from an extensive review of literature and state of the art (Chapters 2 and 3), it has been identified in this research that no studies have been undertaken to investigate the effectiveness of VR as a communication tool in the workflow of the FFE sector. Therefore, the aim of this research was to develop and test novel, virtual environments for immersive communication between the FFE sector and its construction project stakeholders. Furthermore, pre-conditions for the successful implementation of the developed immersive applications were evaluated in the study through experimentation. Cumulative evidence from the literature review in Chapters 2 and 3 revealed that to achieve the objective of this study, it was necessary to develop VR applications with three key functionalities that are vital for effective immersive communication in the FFE sector, namely: BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (distributed interaction). Also, various challenges and benefits associated with the implementation of VR in the FFE sector were identified in the literature review (discussed in detail in the sections below). Identifying these challenges and benefits assisted in evaluating preconditions for the successful implementation of immersive applications in the FFE sector (Chapter 7). The development and testing of the two VR applications were addressed in chapters 4, 5 and 6. Furthermore, it was imperative to validate the industry-wide utility and usefulness of the two VR allocations developed, as addressed in Chapter 7. Also, the challenges and benefits identified in Chapters 2 and 3 assisted in evaluating the pre-conditions for the successful implementation of the developed immersive applications in the workflow of the FFE sector (Chapter 7). In the sections below, the key findings from this study are discussed in detail with reference to the literature.

8.3. Areas of application in FFE

8.3.1. Relevance of immersive visualisation

Effective arrangements of FFE for a facility involve problem-solving and critical decision-making to meet the demands and expectations of the clients/end-users and to respond to their needs through innovative and new design perspectives. This places a huge responsibility on the designers/architects to design the space with utmost care so that the result satisfies the end-user's needs both aesthetically and functionally. However, the design communication and decision-making process in the FFE sector is typically a complex process involving consideration of various constraints such as cost, space availability, quality and aesthetics (Oh *et al*., 2010). Such a complex and vital decision-making process results in uncertainty among the stakeholders over whether they have made the right choice. One of the reasons for this uncertainty is the stakeholders' inability to experience the spaces while they are being designed. Hall and Tewdwr-Jones (2010) reported that communication issues that emanate between various stakeholders during the planning phase of a project are mainly as a result of poor presentation and visualisation of the information. Furthermore, poor stakeholder communication between the FFE designers and, on the other hand, project architects, contractors, clients and facility users can lead to misaligned expectations which further exacerbate understanding of design intent and expectations, thereby contributing to project failure as a result of the dissatisfaction. In this context, interesting insights were gained from this research into the effectiveness of an immersive interactive and distributed virtual environment in FFE design communication and coordination compared with the traditional methods (2D-based methods) practised throughout this industry (Chapters 4, 5 and 6). The findings from this research revealed a higher level of user satisfaction in a virtual environment compared with the 2D-based methods. Papagiannidis *et al*. (2013) noted that satisfaction is a key ingredient in building consumer loyalty, and end-user satisfaction is a major goal in every user-system interaction. It is noted that user satisfaction is the ultimate element that triggers the user's intention to purchase a product or accept a design, and this has been proven empirically in various studies (Papagiannidis *et al*., 2013).

Another important finding of this research was the effect of co-presence on the FFE stakeholders during communication of design whilst in the virtual environment. FFE stakeholders considered the human-human interaction offered by distributed VR (DVR) applications developed for this study to be highly effective in evoking positive communication and interaction in the virtual environment. This was affirmed in the validation phase (Chapter 7), in which co-presence was identified as an important factor that can facilitate the adoption of immersive VR applications similar to the DVR developed for this study. This concurred with the findings of previous studies (Liu and Kaplan, 2018; Oliver, 2019) leading to the conclusion that co-presence in VR can be considered as the antecedent of effective communication among the stakeholders. This finding also contradicted the findings of Mahdjoubi *et al*. (2014), who found that co-presence using avatar representation did not have any effect on the users. However, this result might have been influenced by the type of VR environment (exploratory VR) used in their study. The findings from the current study applied not only to design decisions using VRin the construction industry but also in multi-dimensional aspects, such as v-commerce or virtual FFE showrooms, which enable users to immerse themselves remotely and to purchase FFE elements confidently based on the design choices they make in the virtual environment (Chapter 6). This possibility was affirmed by the findings of this research (Chapters 5 and 6), which revealed that visualisation in immersive environments can enhance confidence, trust and satisfaction and can reduce the disappointments of the clients/end-users of the FFE sector. It was also found in this research that immersive communication reduces the time required to complete the FFE design task (Chapter 4). This was evident from the significant difference in the time taken to complete design decisions using traditional methods compared with using immersive and interactive VR design. Also, decisions made using the paper-based method changed when the participants performed the same task in the virtual environment (Figure 4.8). This is because spatial perception plays a key role in the context of understanding an architectural space and using that space effectively. Spatial perception is a complex, internal, information-processing task (Marr, 1982), the goal of which is to estimate, identify, recognise and give meaning to objects and spaces with which humans interact (Palmer, 2003) which, in the context of this study, was human-FFE interaction. It has been observed in other studies (Paes, 2017) that better spatial perception leads to an enhanced interpretation of spatial elements, which leads to the conclusion that, within the immersive virtual environment, displaying spatial geometric information about the FFE elements facilitates better understanding and is processed better by the user. However, in the case of paper-based methods, the chances of acquiring such spatial perception are nearly impossible. This finding is noteworthy because many of the participants in this study had more than 25 years of experience in FFE product design, manufacture and spatial planning using traditional methods, yet they preferred a different design choice in the virtual environment. Based on the findings from this study, it can be concluded that immersive visualisation in the FFE sector plays a vital role in design communication, which traditional methods cannot offer. This is underpinned by the capabilities offered by immersive visualisation for a better understanding of the impact of FFE design decisions and problem-solving and making faster and more informed iterations.

8.4. VR development for FFE

8.4.1. Tools and techniques

One of the major challenges that limited the utilisation of VR technologies in the workflow of the AEC industry generally was the complexity of developing VR environments. However, with the recent advancements in software and hardware, VR development is no longer an uncharted area. Berg and Vance (2017) observed that the current state of VR is "mature, stable and importantly usable" in the AEC sector. Various tools, approaches and techniques have started to emerge recently that have aided in initiating the development of VR environments from a lower entry point. Some of the popular tools that have emerged and rendered the development of a VR environment possible are intuitive game development engines such as Unity3D, Unreal Engine and CryEngine. Unity3D was used in this research because of its ease of integration with VR platform-specific SDKs and customisability with APIs. These advancements in SDKs have also aided VR developers to create VR environments without having to target any specific VR platforms. One example of such SDKs is the XR integration toolkit, which is a high-level component-based interaction system that allows cross-platform integration. This integration can improve development workflow considerably as well as reduce the time required for VR development. This was evident from the comparison of the number of iterations and complexity of the development of interactive VR (Chapter 4) that was not built using the XR integration toolkit and COFFEE/DVSE (Chapters 5 and 6) with the development of interactive VR using the XR development toolkit. Even though the development of VR for the AEC industry has become comparatively straightforward, various challenges still exist that make the development process cumbersome for the AEC industry generally, and the FFE sector specifically. The tools and techniques for VR development available currently are focused more on the gaming industry. For instance, the development of a virtual 3D environment for the FFE sector is a challenging process compared with the gaming industry because of interoperability issues and the post-processing optimisation required for a smooth virtual experience for the users (discussed in the section below). Even though the tools and techniques used for the development of VE have undergone tremendous transformation in terms of accessibility and ease of implementation, several challenges were also identified in this research that still exists in the development process that can affect the future adoption of VR in the FFE sector. In the sections below, some of the key, VR development challenges identified in this research are discussed with reference to the literature reviewed and empirical studies.

8.4.1.1. Data exchange and interoperability

One of the major challenges (Chapter 3) associated with the adoption of VR in the AEC industry as a whole was associated with the complexities of data exchange and interoperability issues (Prabhakaran *et al*., 2022). This challenge was particularly critical for the FFE sector that operates on low-profit margins (Prabhakaran *et al*., 2021) which impaired this sector's intention to adopt digital technologies such as VR (Prabhakaran *et al*., 2022). However, recent advancements in software and hardware have resulted in addressing these VR development challenges, making them more straightforward than they were earlier. For instance, during the development of the interactive VR application (Chapter 4, Figure 4.2), the development workflow was a cumbersome process involving multiple iterations in which it was necessary to convert 3D models of FFE elements, developed in BIM authoring tools, into "Film Box (fbx}" format before importing them into the Unity3D game engine. Even though BIM authoring tools, such as Revit can generate FBX files that can be imported directly into a game engine, the meta-data translations were resource-demanding and not straightforward. Even though this workflow has eased the flow of the BIM model into the game engine, the iterations required in this process are comparatively cumbersome. This process also limited the flow of semantic information which is essential for design communication and decision-making in the FFE sector. In addition, this process is time-consuming, and resource-demanding and the possibilities of data omission (graphical and non-graphical) are high. Furthermore, for effective interoperability and accurate data exchange, a bi-directional flow of information between the modelling tool and the VE development engine is imperative. However, it has been observed in some studies (Lehtinen, 2002; Du *et al*., 2018) that there is no streamlined process for importing or exporting geometry between CAD software and game engine. Also, in previous studies (Yan *et al*., 2011), the need for middleware applications, such as Autodesk3D's max, was highly emphasised for the meta-data translation. These issues are a major concern for the FFE sector, which was evident from the responses of some of the FFE stakeholders during the testing of the VR applications developed for this study (Chapters 4, 5 and 6). In this context, the workflows proposed and findings from this research will be highly beneficial not only for the FFE sector but also for the AEC industry as a whole because the methodology adopted in this research for the seamless transfer of graphical and non-graphical information into the game engine and the resulting VE development process is novel. During the development of COFFEE (Chapter 5) and DVSE (Chapter 6), Unity3D's native plugin, "Reflect" (Unity3D, 2021), was used as the inter-operability enabler (Figure 5.3), which served two critical functions in the development: *a)* Meta-data translation from the BIM authoring tool to the game engine; *b)* BIM model optimisation before being imported into the game engine. This BIM model optimisation process aided in reducing the number of polygons[1] present in the BIM model, thereby eliminating the computational load of the graphic rendering, and eliminating possible frame rate drops and network delays. For the FFE sector, the BIM to VR workflow using Unity3D's native plugin, "Reflect" (Unity3D, 2021), is particularly beneficial because of the live link between the Unity3D

[1] Polygons are the collection of vertices, edges and faces that defines the geometry of that 3D model.

game engine and the Autodesk Revit, using Reflect. This live link with the central BIM model through the Unity Reflect interoperability plug-in enables the stakeholders to update the FFE models in the game engine without having to re-import the affected elements. Instead, any updates made on the central BIM model are synchronised automatically. One of the factors that affect the adoption of the proposed approach to enabling data exchange and inter-operability will be accessibility to the software which supports these processes. The cost associated with this software will be a burden for a sector such as FFE which already operates on a low-profit margin and has been disrupted by post-COVID financial implications (Prabhakaran et al., 2021). The impact of these challenges is discussed further in Section 8.6.

8.4.1.2. Interactivity and distribution in the VR environment

With the introduction of BIM, the synergy between the 3D information-rich model and the virtual environment has become straightforward. For instance, the use of rendering engines, such as Enscape, which integrates with BIM authoring tools, such as Autodesk Revit, has enabled the creation of a virtual environment that is straightforward for FFE stakeholders such as architects and FFE designers. However, there a strong concern exists in the FFE sector that the current utilisation of VR applications compromises the full potential of VR because the environmental representation is focused predominantly on the visual modality, regardless of other endless possibilities such as utilising attached meta-data to interact and manipulate the information-rich BIM model and improve the decision-making process through remote collaboration (Prabhakaran *et al*., 2021; Yoon *et al*., 2010). Therefore, existing VR applications might be limited in ensuring full walk-throughs and visualisation of the construction sequence, which are examples, however, of key user requirements in FFE design or construction communications (Greenwood *et al*., 2008;

Johnson *et al*., 2010). This poses an additional challenge, as the knowledge and research of what constitutes an efficient and effective visualisation, collaboration and communication tool lag behind the rapidly evolving technology (Johnson *et al*., 2010; Wen and Gheisari, 2020). In order to create such an interactive and intuitive virtual environment, one of the core skill requirements is the programming (algorithm) skills that enable human-machine interactions. Developing an algorithm (script) that will enable functionalities such as interaction and manipulation in the virtual environment is one of the major challenges during VE development. Different from other industries, such as the manufacturing and automobile sector, every project is unique, and so are the requirements of the FFE stakeholders. Therefore, to enable the virtual environment and the related functionalities to meet the stakeholders' requirements, each project requires tailored algorithms. Moreover, the development of a virtual environment that is interactive, informative, intuitive, immersive and illustrative requires specific development skills (Chapter 3). Any job or trade inevitably changes over time and the required skillsets are also subject to change. With the FFE sector embracing a faster and more accurate process, there is a clear need for related professionals to remain up-to-date with programming skills. Advancements in software technology are also assisting this process. For instance, visual scripting features available for game engines, such as Unity3D and Unreal, can aid in creating logic for VE development that both skilled and unskilled developers can use without the need to write programmes. Although these visual programming features have been implemented broadly in other industries, their implementation and utilisation in the AEC industry are fairly new (Kensek, 2015). However, visual scripting applications, and programming interfaces, such as Dynamo which is currently used alongside BIM authoring tools, are helping to bridge the skills gap in the FFE sector. Over the years, there have been constant changes in the way in which the FFE sector works, and it is evident that this sector is very accepting of new and innovative methods.

8.4.1.3. Environment fidelity and model optimisation

Human beings have a bias toward vision, as we take in most of our sensory information about the environment through the visual sense (Jerome, 2006). This raises the question of "How real is virtual reality?", which often raises weighty metaphysical issues and, at the same time, poses a very practical challenge for both the research community and industry partners seeking to use VR for design communication and decision-making. It has been suggested in studies (Cooper, 2018) that the effectiveness of a VE is closely related to the fidelity of the environment. The user experience must be at the forefront of any evaluation process while investigating the usability feedback signals in VR-based, immersive communication systems (Cooper, 2018). The acceptability of an immersive VE is primarily determined by these feedback signals that are present during the interaction in the VE (Cooper *et al*., 2018). The Fidelity of the VE is often considered in the assessment scale for evaluating the effectiveness of any VE. Meyer *et al*. (2012) defined fidelity as "a measure of the degree to which a simulation system represents a real-world system". Thus, the fidelity of a VE could be viewed as the faithfulness of a simulation, where the degree of this simulation looks, feels and acts like a real-world environment (Cooper *et al*., 2018). In the context of FFE sector design communication and decision-making, this environmental fidelity has greater meaning because the virtual environment must be realistic enough to immerse the user in order to trigger realistic responses (Ragan *et al*., 2015). Based on the current research (Chapter 4), it was identified that aesthetics plays a major role in making procurement decisions in the FFE sector. This emphasises the importance of the fidelity of VE. Similarly, it has been suggested in studies that a high level of environment fidelity has a positive impact on the stakeholder's understanding of the design and, thus, the cognitive process (Mourkoussis *et al*., 2010). However, achieving such a higher level of visual fidelity in the virtual environment is a resource-demanding task, as it is necessary to re-texture the materials of the model imported from the BIM authoring tool. Ragan *et al*. (2015) noted that photo-realistic texturing is an effective way of providing a high-fidelity, virtual environment. In the workflow proposed in Chapter 5, Unity3D's high-definition rendering pipeline (HDRP) was used, which offers a scriptable, rendering pipeline together with a material enhancer application, called Quixel Mixer (Quixel, 2021), which provides the methodological frameworks (Figure 5.5) for the FFE sector to achieve realistic VE. One of the challenges faced during the process of texture mapping was the incompatibility between Unity3D's HDRP and the VR integration package which failed to identify the material of the VR controllers. To overcome this challenge, a custom shader graph was developed using Unity3D's shader builder, which was then applied as the controller's default shader graph. A critical factor to consider while developing such a realistic environment is the processing capability of the HMD which will have a direct impact on the user experience because of the drop in frame rate. In this research (Chapter 7), achieving a high frame rate was identified as one of the critical challenges that could affect the adoption of VR. Even though tethered HMDs, such as HTC Vive, are capable of achieving a high level of visual realism, standalone devices, such as Oculus Quest, require optimal models to deliver a realistic user experience. This is a major challenge for a sector such as FFE which operates on low-profit margins, because the high-performance HMDs are costly, which was identified in this research (Chapter 7) as the topmost challenge that can affect the adoption of VR in the FFE sector. However, with the chip revolution and advancements in ICT, it can be expected that hardware and software costs will reduce considerably.

8.5. Key VR approaches for FFE

From an extensive review of the literature and state-of-the-art practices (Chapters 2 and 3), it was identified that no studies had been undertaken to investigate the effectiveness of VR as a communication tool in FFE workflow. There is a strong concern in the FFE sector that the current utilisation of VR applications compromises the full potential of VR because the environmental representation is focused predominantly on the visual modality, regardless of other endless possibilities such as utilising attached meta-data to interact and manipulate the information-rich BIM model and improving the decision-making process through remote collaboration (Prabhakaran *et al*., 2021; Yoon *et al*., 2010). This poses an additional challenge because the knowledge and research of what constitutes an efficient and effective visualisation, collaboration and communication tool lag behind the rapidly evolving technology (Johnson *et al*., 2010; Wen and Gheisari, 2020). Based on the review of the literature (Chapters 2 and 3). It was found also that the current state of the VR application in the FFE sector lacks three critical advancements, namely: BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (multi-user interaction). In a bid to address this gap, two VR applications a) Interactive VR applications and b) distributed VR applications were developed and tested in this research for their effectiveness, usefulness and usability in both the construction and retail segments of the FFE sector. The findings from the testing of these novel VR applications are discussed in the sections below.

8.5.1. Distributed immersion

While many of the studies so far have been focused on understanding the potential of VR during the appraisal of the interior design of a building, various technical limitations exist in the current state of VR that could restrain the full-scale application and adoption of this technology. One of the most critical issues is related to the inability to have a collaborative virtual environment in which a group of geographically remote stakeholders can interact, communicate effectively, and appraise designs collaboratively in real-time (Roupé *et al*., 2020). This limitation has not been addressed because the development process for such distributed VR applications is complex and the infrastructure requirements for such developments are resource-demanding (Podkosova *et al*., 2016). The amount of time that occupants spend indoors (90 %) emphasises the significance of FFE and its effective arrangements in influencing human experience within a built space, which demands a collective decision-making environment. A novel methodology was proposed in this research for the development of two distributed VR environments, namely, COFFEE and DVSE (Chapters 5 and 6) which were tested to address this limitation of the current state of VR applications in the fields of both construction and the retail supply chain of the FFE sector. The findings from the testing of COFFEE and DVSE are discussed in the sections below.

8.5.1.1. Collaborative Furniture Fixture and Equipment Environment (COFFEE)

In order to understand the usability of COFFEE, a series of usability trials were carried out using the system usability scale proposed by Brooke (1996) (Table 5.1). The mean SUS score obtained for COFFEE was 79, which was above the recommended threshold of 70, suggested by Bangor *et al*. (2009) and Brooke (1996), for technology to be considered acceptable. Based on the adjective rating proposed by Bangor *et al*. (2009), the usability score for COFFEE fell between “good” and “excellent” (Figure 5.9), thus indicating that the stakeholders considered COFFEE to be easy to use, easy to learn and robust. In general terms, it was interesting to note that the four lowest scores (PA1, PA2, PA23, PA24) were from the participants who were above 50 years of age, and some of the highest scores were from participants below 40 years of age, suggesting that the comparatively younger users were probably more comfortable with technologies such as virtual reality, which concurred with the findings of Bottani *et al*. (2021). Furthermore, it was noted that some of the highest scores were from the architects, followed by FFE designers and contractors. It was noted that, during the validation phase of COFFEE, architects, FFE designers and contractors were identified as the stakeholders with the highest intention to adopt COFFEE or a similar application. The usability score for COFFEE indicated the acceptance of COFFEE by potential frequent users who found COFFEE to be useful and easy to use. Also, no significant differences in scores were identified when comparing genders ($p > 0.05$). It has been noted in some studies (Lin and Chen, 2013) that gender differences affect the perceived usability of technology. However, Bangor *et al*. (2008) identified no differences in the rating of the usability of products based on gender, which affirmed the findings of the current study. The participants' perceived sense of presence (SoP) whilst using COFFEE was also measured because it was suggested in extant research (Busch *et al*., 2014; Brade *et al*., 2017; Lorenz *et al*., 2018; Krassmann *et al*., 2020) that the sense of presence in the virtual environment has a strong connection with the usability of the system and will encourage the acceptance of VR technology. Hence, measuring participants' sense of presence (SoP) while using COFFEE was relevant. The Independent Television Commission Sense of Presence Inventory (ITC-SOPI) developed by Lessiter *et al*. (2001) was used to measure participants’ SoP whilst using COFFEE, focusing on the four key constructs: a) sense of physical space, b) engagement, c) ecological validity and d) negative effect (refer to Section 5.7 for further details). Table 5.1 shows details of the ITC-SOPI (Lessiter *et al*., 2001) scores for each of the SoP constructs, suggesting that COFFEE had no, or very low, negative effect (NE) (1.30) as well as a high sense of physical space (SPS), engagement (E) and ecological validity (EV). The results shown in Table 5.1 suggested that the participants' SPS in COFFEE scored the highest (4.12), which meant that participants had a higher feeling of "being there" while interacting with the FFE elements and the stakeholders. The EV score was the second highest (4.05), which suggested that the users felt that the virtual FFE environment delivered by COFFEE was sufficient to replicate a response similar to the real-world environment. Furthermore, users showed good engagement (4.00) within COFFEE, which suggested good involvement and interest in the content delivered by COFFEE.

In addition, findings indicated that the usability of COFFEE can be affected by the negative effects caused by the VR environment, such as motion sickness, dizziness etc. This concurred with the findings of a previous study (Mousavi *et al*., 2013), which indicated that it is necessary to take utmost care during the process of developing a VR environment to reduce the negative effects of VE. However, the other three SoP constructs showed a low or insignificant correlation to usability. This contradicted the findings of Busch *et al*. (2014), using the CAVE environment, but supported the findings of Brade *et al*. (2017) using a real-world environment. It is noted that HMD-based VR systems are capable of providing a more realistic and engaging experience than a CAVE system (Mallaro *et al*., 2017; Elor *et al*., 2020), which sometimes is sufficiently closer to a real-world environment, which suggests that, apart from the negative effects, no other SoP factors could potentially affect the usability of a system similar to COFFEE that provides a comparatively similar realistic and engaging experience to that of the real world.

Further qualitative interviews were conducted also with 15 FFE experts who agreed to participate in an open-ended interview to obtain further options (Table 5.1). The interview data collected were analysed using thematic analysis which is often referred to as the most efficient method in analysing qualitative data to capture valuable information (Braun and Clarke, 2006). Based on the thematic analysis, four themes were identified: a) Usefulness, b) functionality, c) general attitude and d) challenges. In terms of the usefulness of COFFEE, all the participants (n = 15) considered COFFEE to be a useful tool for improving the communication of design in FFE. Participants (n = 3) noted that, typically, communication of design in FFE is a cumbersome process involving technical and non-technical stakeholders utilising mostly 2D-based designs that result in several design changes throughout the projects. However, with the utilisation of COFFEE in the design communication process of FFE, it is easy for all the stakeholders to be involved in the early design process, in an immersive environment that provides them with the opportunity to understand the design, thus limiting costly design changes. Based on the opinion of the FFE experts, COFFEE could be a game-changer in enhancing collaborative design communication with stakeholders, regardless of their comprehension capabilities. This affirmed the findings of Chalhoub and Ayer (2018) and Du *et al*. (2018), who observed that the opportunity for early involvement of stakeholders (technical and non-technical) is one of the most important factors that encourage the adoption of distributed VR applications. The results from the validation of COFFEE (Chapter 7) also affirmed these findings from expert interviews. The majority of the participants (57.26%) considered COFFEE to be extremely useful, and 35.04% and 31.62% of respondents considered COFFEE to be very useful for design communication and collaboration in FFE. Figure 7.7

illustrates the respondents' perceptions of the usefulness of COFFEE for design communication and collaboration in FFE.

All the participants (n = 15) commented positively about the various functionalities of COFFEE. Specifically, participants commented very favourably about the multi-user functionality which makes COFFEE unique from other VR-based design communication systems currently available. Participants (n = 8) commented on the responsiveness of the interface and the method adopted to design it like a tablet interface. Two of the participants commented about the appearance of the avatar representation within COFFEE. It is noted that, in studies in which the influence of avatar realism on users' experience in the virtual environment was investigated (Heidicker *et al*., 2017), it was found that motion-controlled avatars with less realism (similar to the one used for the current study) produced an increased feeling of co-presence as well as positive communication and interaction in the virtual environment. Also, since COFFEE was developed for multi-platform deployment (HTC, Oculus Quest etc.), elements that place a demand on computational resources that did not affect the task were deliberately avoided. Furthermore, all the participants (n = 15) opted for teleportation as the preferred means of navigation in the virtual environment, which affirmed the findings of Boletsis and Cedergren (2019). One of the participants (P13) noted that nausea was experienced while using physical locomotion, which led to switching to teleportation mode, which confirmed the findings of Buttussi and Chittaro (2021). Furthermore, all the participants (n = 15) showed a positive attitude toward the concept of COFFEE. Participants identified COFFEE as an innovative tool that could improve the productivity of the FFE sector. Participants (n = 6) also mentioned that they would highly recommend COFFEE for use in their upcoming projects. Participant (P10) mentioned the possibility of demonstrating the potential of

COFFEE to their clients so that COFFEE could be included in their projects for early-stage design. Mahamadu *et al*. (2022) noted that VR-based applications are highly efficient in supporting participatory design when the views of elderly end-users are sought during the design process. However, one of the challenges of such VR applications is the feeling of isolation whilst in the virtual environment, especially when the users belong to a vulnerable population. In this context, the application proposed in the present study can eliminate these challenges through the sense of co-presence. Also, in general, Kim and Jo (2021) observed that co-presence in the virtual environment can highly improve the productivity and satisfaction of participants in the design process, and encourage the adoption of the application.

FFE experts also noted some challenges that might constrain the full-scale deployment of systems similar to COFFEE. One of the critical challenges about which participants (n = 8) were concerned was the cost of adding virtual reality-based technology into the workflow of FFE. It is noted that the challenge posed by the cost of VR has been reported in many studies, as identified in Chapter 3, which was reiterated during the testing (Chapters 5 and 6) and validation (Chapter 7) of COFFEE. The participants perceived cost as the topmost fact that could affect the adoption of VR applications such as COFFEE. Although the recent advancements in hardware and software technology have made VR peripherals more accessible, it has been suggested that providing a high-quality VR environment still requires high-end computer systems with advanced processing units to run them, with additional application development costs (Garrett *et al*., 2018; Du *et al*., 2018). As with information technology, attrition of value is also rapid; older systems become obsolete with the rapidly emerging newer technology.

Also, the skills required to develop a VR environment are another challenge that experts (n = 4) believed could affect the development and adoption of systems such as COFFEE. Even though this challenge has been reported in minimal literature (n = 11) (Chapter 3, Figure 3.8), it was identified during the validation phase of COFFEE (Chapter 7) that the FFE sector considers this to be the most critical challenge that can affect the adoption of immersive VR applications such as COFFEE. As commented by an FFE expert above, the FFE projects operate mostly on narrow profit margins, which limits them from recruiting developers solely for VR development. Adding basic programming modules to education programmes for construction is a possible opportunity to develop professionals with multiple skillsets, which would help sectors, such as FFE, to recruit multi-skilled professionals without incurring a financial burden.

Furthermore, some participants (n = 4) identified inter-operability as a challenge that could affect the adoption of such technology. Inter-operability was the most reported challenge in literature (n = 26) (Chapter 3, Figure 3.8). During the validation phase of COFFEE, in the maturity of the technology category (Chapter 7, Table 7.7), FFE stakeholders considered inter-operability to be the second most critical challenge that can affect the intention to adopt applications similar to COFFEE in the FFE sector. Until recently, several iterations were required for the transfer of BIM models into the game engine, as reported in several studies (Du *et al.*, 2018; Chalhoub and Ayer, 2018). However, the recent integration of inter-operability plugins, such as Unity Reflect (similar to the one adopted for the current study) is making the data exchange process far more streamlined than before. However, this also raises the earlier cost constraint mentioned by the experts. Acquiring the licence for the development engine and inter-operability tools can add further costs for the FFE sector.

8.5.1.2. Distributed virtual shopping environment (DVSE) for the FFE sector

The DVSE was tested among stakeholders (n = 9) from the retail, product showcasing and sale context of the FFE sector. The thematic analysis of the interview with the stakeholders, after using DVSE, revealed a positive overview of DVSE. The key themes identified were categorised according to the Technology Acceptance Model (TAM) constructs and are reported in Table 6.2. All the participants (n = 9) considered the DVSE to be practical, helpful and relevant to the FFE sector with regard to the perceived usefulness construct. Even though COFFEE and DVSE are targeted at two different segments of FFE (construction and retail, respectively), the fundamental functionality of both applications is similar. Furthermore, a key finding from the testing of DVSE was that interactivity offered by DVSE had a significant impact on participants' responses. This finding agreed with the study of Mahdjoubi *et al*. (2014). In addition, all six participants who tested the application considered DVSE to be interactive, simple, and responsive. However, some participants (P1, P2, P6 and P8) reported motion sickness while using the joystick locomotion method, which affirmed the findings of (Mahamadu *et al*., 2020). All the participants (n = 6) preferred teleportation as the locomotion method. During the testing of COFFEE (Chapter 5) and interactive VR (Chapter 4), the majority of the stakeholders preferred teleportation as the locomotion method. All six participants who used DVSE identified the avatar representation as a critical engagement factor that delivers a “sense of being” in the virtual environment. This concurred with the findings of Casanueva and Blake (2001) and Söeffner and Nam (2007). However, it contradicted the finding of Mahdjoubi *et al*., (2014) which suggested that avatars might not have any impact on the user's experience and engagement. This could be attributed to the type of virtual environment (exploratory VR) used for their study, which is incapable of delivering a sense of embodiment (Matamala-Gomez *et al*., 2019). Also, all the participants (n = 9) commented on the multi-user functionality, the significance of which cannot be over-emphasised in view of the social distancing restrictions as a result of the COVID-19 pandemic. With regard to the GA construct, all the participants (n = 9) considered DVSE to be: great, innovative, efficient, productive and novel. All participants considered DVSE to be worth recommending, useful, and meaningful. One participant commented, "We definitely would like to develop DVSE further to incorporate all our product range and to recommend to all our supply chain". It is noted that the challenge posed by the cost of VR has been reported in many studies, as identified in Chapter 3, which was affirmed during the testing (Chapters 5 and 6) and validation (Chapter 7) of DVSE. With the recent chip revolution and advancements in information technology, it is expected that, in the coming years, extended technology peripherals will be more accessible to the general population (Dingman, 2020).

8.5.2. Interactive immersion

Rapid developments in ICT, especially immersive technologies, i.e. virtual, augmented and mixed reality (VR/AR/MR applications), have offered new opportunities to address the communication and engagement gap in the FFE sector, which has offered a reliable extension of BIM for more advanced visualisation as well as communication (Rasmussen *et al*., 2017). Despite the potential of BIM-based ImT, there are few examples of their application within the FFE sector. Notwithstanding the well-documented potential of ImT in the FFE sector, some limitations with current applications have been highlighted in reports as being merely an over-glorified extension of traditional 2D communications. Thus, the full potential of data-rich BIM models integrated with ImT has not been realised to its fullest extent yet. In bridging this gap, the effectiveness of an interactive immersive VR environment in enhancing the stakeholders' communication and resulting understanding of an FFE product design choice for a facility was explored in this research (Chapter 4). A novel methodology was proposed for the development and application of an interactive virtual environment in FFE design communication which was tested further among FFE stakeholders for its effectiveness. One-group pre-test-post-test design was adopted because of its suitability in understanding the behavioural factors in determining the effect of the treatment on a given sample. The testing revealed interesting insights into the effectiveness of a VR-based, interactive, FFE virtual environment in FFE design communication and coordination compared with traditional methods (2D-based methods) practised throughout this industry. Time taken to complete the presented task (Table 4.2) suggested that FFE design choices made using the virtual environment required significantly less time compared with the 2D-based methods. This concurred with the findings from the literature review (Chapter 2) and the validation phase (Chapter 7) of the interactive VR application, where FFE stakeholders considered speedy design decisions and time-saving to be two important benefits that VR can offer to the FFE sector that can encourage the adoption of VR further in the FFE sector. These findings also suggested that, if there is no sacrifice in the quality of the design choice, there is a direct benefit in using VR as a tool for enabling effective design communication among the critical stakeholders. Furthermore, this result complements the findings of Wang and Dunston (2007), who suggested that the use of VR HMD shortens the completion time with the less cognitive workload for a task which demands spatial orientation that requires local situation awareness. This finding has a high significance because the FFE stakeholders who took part in this study were very familiar with the paper-based method of design communication. However, it was noteworthy that the performance on the VR-based task was significantly better than the paper-based task, even though the participants had no, or very little, experience with VR.

The experiment also revealed that all the design decisions made using the paper-based method changed when the participants performed the same task in the virtual environment (Figure 4.8). This was because spatial perception plays a key role in the context of understanding an architectural space and using that space effectively. Spatial perception is a complex, internal, information-processing task (Marr, 1982) the goal of which is to estimate, identify, recognise and give meaning to objects and spaces with which humans interact (Palmer, 2003), referred to as human-FFE interaction in the context of this study. It has been noted in studies that better spatial perception leads to an enhanced interpretation of spatial elements (Paes, 2017), which leads to the conclusion that, within the immersive virtual environment, displayed spatial geometric information about the FFE elements facilitates better understanding and is processed better by the user. However, in the case of paper-based methods, the chances of acquiring such spatial perception are nearly impossible. This finding is noteworthy because many of the participants in this study had more than 25 years of experience in FFE product design, manufacture and spatial planning using traditional methods, yet they preferred a different design choice in the virtual environment. This study also revealed a higher level of user satisfaction in a virtual environment compared with the 2D-based method. Papagiannidis *et al*., (2013) noted that satisfaction is a key ingredient in building consumer loyalty, and end-user satisfaction is a major goal in every user-system interaction. It is noted that user satisfaction is the ultimate element that triggers the user's intention to purchase a product or design, and this has been proven empirically in various studies (Papagiannidis *et al*., 2013). The findings from this study could be applied not only in making design decisions using virtual reality, but also in multi-dimensional aspects such as v-commerce or virtual FFE showrooms which allow users to immerse themselves remotely, and purchase FFE elements confidently based on the design choice they make in the virtual environment.

8.6. Design Specifications for the development of an Ideal VR system for the FFE sector's use

It is evident from this research that VR is a viable tool for design communication and coordination in the FFE sector. It was also identified that certain challenges can have a profound impact on the adoption and utilisation of VR systems in the FFE sector specifically and the construction sector generally. To develop an ideal VR system, it is important to consider various factors starting from modelling the virtual environment to enabling interaction and visualisation. From this study, it was identified that Autodesk Revit is a viable tool for modelling virtual environments due to the ease of transferring graphical and non-graphical information using the Unity Reflect interoperability enabling tool. Further Unity 3D was identified as the ideal game engine due to the comparative ease of use, gentle learning curve and extensive online resources. Also, the compatibility of C# programming language makes Unity3D an ideal game development engine. Also, with the integration of Unity's XR integration toolkit, the development of VE can be achieved without targeting any specific VR devices. This capability also addresses the challenge of the cost associated with developments targeting specific VR output files. Furthermore, a low-latency multi-user platform called "Photon cloud" (PUN), which is based on a client-to-server architecture was identified as the ideal multi-user enabling platform. Photon cloud is also a room-based system allowing multiple users to join the same room remotely from any part of the world. The utilisation of the Photon networking engine enables scaling of the virtual environment seamlessly and automatically regardless of the number of users present in the network. The FFE sector can adopt the above-specified tools and techniques to streamline the VE development workflow thus enabling an ideal system development workflow. However, it is worth noting that some of the software specified can incur additional costs due to the licensing requirements.

8.7. Implementation

It was identified in this research that, with the advanced capabilities of distributed and interactive immersive visualisation, VR is changing the way humans interact with visual information dramatically. Although the FFE sector is well placed to gain competitive and operational advantages from the use of distributed and immersive interactive visualisation techniques, the diffusion of VR applications in this sector has followed a steep curve. Despite the UK Government's investments (£72 million) and promotions to adopt VR technology in the AEC industry (Gov. UK, 2018), being a low technology-oriented sector, FFE has fallen behind in embracing VR (The British Furniture Confederation, 2018). This could be attributed to a myriad, of complex and inter-related factors that are very difficult to understand and, consequentially, the implementation of any mitigation plans cannot be devised. One of the objectives (Objective 5) of this research was to evaluate pre-conditions for the successful implementation of the developed immersive applications through experimentation. Thus, in this research, the factors and challenges that affect the adoption of VR in the context of FFE were identified (Chapter 7) through an extensive literature review (Chapters 2 and 3) and through the development and testing of the distributed (Chapters 5 and 6) and interactive (Chapter 4) VR applications. Furthermore, drawing upon these factors, the "what" and "how" of various determinant antecedent conditions that facilitate or inhibit the implementation of the two VR applications developed for use in various FFE contexts were explored further in this research, particularly for design communication and co-ordination. Based on the research, 29 challenges and 25 benefits that can affect/facilitate the implementation and adoption of interactive and distributed VR applications developed in this research were identified (Chapters 4, 5 and 6). To simplify the complexity of a large number of data sets further, each of the VR implementation factors was categorised into components constituting various dimensions (Chapter 7, Table 7.7 and 7.8).

8.7.1. Challenges affecting the adoption of virtual reality in the FFE sector.

Based on an extensive literature review (Chapter 3), perceived cost was identified as the sixth most-reported challenge of implementing VR in the A and C industries. However, FFE sectors consider perceived cost to be the topmost challenge that affects the implementation of VR, as identified in Chapter 7. This could be attributed to the narrow profit margin on which the FFE sector operates (Prabhakaran *et al*., 2021) and any additional costs for procurement of hardware such as VR devices, high-performance laptops etc., and software such as virtual environment development game engines and other supporting software, which could affect the sustainability of this sector. While the cost of HMDs has decreased because of the recent advancements in technology, the cost associated with the supporting software, such as game engines, modelling tools etc., and hardware such as a high-performance computer as well as the training/hiring cost of a skilled workforce, is considered to be a major challenge in the adoption of VR technology. The FFE sector also considered a skills shortage to be the second most critical challenge that can affect the adoption of VR. This finding affirmed the arguments of Allen (2019), who noted that the AEC industry as whole faces massive skills shortages which are hampering the adoption of VR technology. In a report by Innovate UK (2019): The immersive economy in the UK, it was suggested that skill shortage is one of the biggest challenges faced by industries in adopting VR. A survey by Mateos-Garcia *et al*. (2019) revealed that 65% of the industry considered skill shortage to be a major challenge. In previous studies also, skill shortage has been reported as a major challenge faced by the AEC industry (Hou *et al*., 2016). Being a low-profit-margin sector, this challenge could pose the same threat as perceived cost, as additional training to up-skill the workforce can severely impact the profit.

Based on the FFE stakeholders' perceptions, the immature technology component was ranked as the third critical VR implementation challenge that can affect the implementation of VR-based technology in the FFE sector. One of the major technological challenges that limit the adoption of VR in the construction sector is the high processing requirement which leads to additional issues regarding the cost and portability of VR devices (Du *et al*., 2018). Similarly, interoperability issues (discussed in Section 8.4.1.1) are another major technological challenge that VR developers in the AEC industry face. The iteration requirements before the virtual environment are VR ready have also been reported in other studies (Chalhoub and Ayer, 2018; Du *et al*., 2018). These challenges also add up to the additional cost required for the middleware software for the iterations. Although a lack of institutional drivers and privacy and safety have been reported in the literature as being critical factors affecting the adoption of VR in practice, FFE stakeholders do not identify these two components as being critical factors affecting their intention to adopt VR.

8.7.2. Benefits facilitating VR adoption and implementation in the FFE context

FFE stakeholders considered improved design communication to be the topmost benefit (Table 7.8) that can facilitate the implementation of VR in their organisations, followed by enhanced user experience, facilitating conditions, and productivity and efficiency. It was also identified that, although the aforementioned factors were considered to be important, productivity and efficiency were the only components that drive the intention to adopt. These findings should be read in conjunction with the findings of The British Furniture Confederation (2018), which noted that the FFE sector being a low technology-adoption industry has resulted in a drastic decline in productivity. This realisation would have resulted in FFE stakeholders' considering VR-based applications for improving the productivity and efficiency of this sector. This argument could be supported further by findings in a report by Barbosa *et al.* (2017), who also highlighted the decline of productivity and performance in the FFE sector, attributing it to the lack of innovation and adoption of digital processes such as BIM (NBS, 2010) and immersive technology (Garcia, 2017). Also, the Industrial Review of TEM (2014) emphasised that the UK's FFE sector has had a low adoption rate of digitalisation and, thus, was facing low productivity and high international competition in its internal market. At the same time, it was highlighted in the report that the FFE sector could benefit from a rapid increase in its competitiveness through digitalisation.

Johnson *et al*. (2010) suggested that any sector of the construction industry should strive to innovate in order to meet the cultural challenge of collaboration and global competition to improve productivity. These reports indicated the necessity for the FFE sector to undergo a drastic amelioration in its current utilisation of technologies to overcome the prevailing inefficiency. This realisation of improvements in productivity and efficiency by using VR could have influenced the respondents' intention to adopt VR technology. However, it is noted that, even though the benefits of the other three components did not reveal any significant correlation with respondents' intention to adopt VR technology, it was identified in this research that these components also influenced productivity and efficiency. It is noted that the level of importance of the factors (challenges and benefits) identified in the literature (Chapters 2 and 3) are different from what the industry considers. This finding indicated that there is a wide gap between the perception of academia and practitioners, highlighting the need for rigour in the research.

8.8. Summary

In this chapter, the results from the development, testing and validation of the interactive and distributed VR applications were discussed with reference to literature and empirical studies. Pre-conditions for the successful implementation of the developed immersive applications in the FFE sector were also highlighted in the discussion. Areas of similarity and divergence from existing literature and knowledge were noted in the discussion.

Chapter 9: Conclusion, Recommendations and Contributions to the knowledge

9.1. Introduction

The aim of this research was to develop and test novel, virtual environments for immersive communication between the FFE sector and its construction project stakeholders. Furthermore, pre-conditions for the successful implementation of the developed immersive applications were evaluated in the study through experimentation. In this chapter, the results from the development and testing are placed in context with reference to literature and empirical studies. The conclusions are discussed in relation to each of the research objectives. In addition, the novelty of this research and the contribution to the knowledge are detailed. The limitations, recommendations, and directions for future research are also noted in this chapter.

9.2. Review of research objectives and key findings

Based on an extensive review of the literature and state-of-the-art practice (Chapters 2 and 3), it was identified that no studies had been undertaken to investigate the effectiveness of VR as an immersive communication and coordination tool in the workflow of the FFE sector. There is a strong concern in the FFE sector that the current utilisation of applications compromises the full potential of VR because the environmental representation is focused predominantly on the visual modality, regardless of other endless possibilities such as utilising attached meta-data to interact and manipulate the information-rich BIM model and improve the decision-making process through remote collaboration (Yoon *et al*., 2010; Prabhakaran *et al*., 2021). This poses an additional challenge because the knowledge and research about what constitutes an efficient and effective visualisation, collaboration and communication tool lag behind the rapidly evolving technology (Johnson *et al*., 2010; Wen and Gheisari, 2020). The current state of VR application in the FFE sector lacks three critical advancements, namely: BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (multi-user interaction). In order to address these gaps, the aim of this research was to develop and test novel, virtual environments for immersive communication between the FFE sector and its construction project stakeholders (Chapters 4, 5 and 6). Pre-conditions for the successful implementation of the developed VR applications were evaluated further in the research through experimentation (Chapter 7). A mixed-method design was used for the empirical evaluation (Section 1.8). Six research objectives were proposed to achieve the aims of the research, as discussed below.

Objective 1: Review state-of-the-art applications of VR in the AEC industry in general and in FFE in particular in order to identify opportunities and areas of application for VR and its use for improving communications and coordination of design in FFE.

This objective was achieved in phase one (Figure 1.1) of the research that is addressed in Chapters 2 and 3. Based on an extensive literature review, it was found that there is a dearth of research on the application of VR as a design communication approach and tool in the FFE sector. The findings of the literature review also revealed that VR has great potential in the FFE sector as a design communication and collaboration tool. Existing VR applications, when integrated with the workflow of FFE, can assist stakeholders to experience the spaces before they are constructed physically and use them as a spatial coordination tool. Also, it was identified that the visual information that is conveyed through the virtual representation is beneficial for the FFE sector because the clients' procurement decisions are affected by information about colour, patterns, visual texture, ergonomics, and material. However, it was noted from the literature that no studies had been undertaken to investigate the effectiveness of VR as a design communication and coordination tool in the workflow of the FEE sector. There is a strong concern in the FFE sector that the current utilisation of VR applications compromises the full potential of VR because the environmental representation is focused predominantly on the visual modality, regardless of other endless possibilities such as utilising attached meta-data to interact and manipulate the information-rich BIM model and improve the decision-making process through remote collaboration. The results of the literature review showed that the current state of the VR application in the FFE sector lacked three critical advancements, namely: BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (multi-user interaction). Furthermore, factors that affect/facilitate the implementation of VR (challenges and benefits) in the FFE sector were identified in the literature review (Tables 7.7 and 7.8).

Objective 2: Ascertain requirements for high-fidelity FFE-specific VR applications and develop the VR applications based on the requirements identified.

Based on a rigorous literature review (Chapters 2 and 3), it was identified that VR applications used in the workflow of FFE lacked certain critical functionalities, namely: human-BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (multi-user interaction) that are essential for effective design communication and co-ordination. The lack of these functionalities posed an additional challenge because the knowledge and research about what constitutes an efficient and effective visualisation, collaboration and communication tool lag behind the rapidly evolving technology. To address these shortcomings of the current VR applications in the FFE sector, two VR applications with a) interactive functionality and b) distributed functionality (COFFEE and DVSE) were developed using the rapid prototyping method in phase two (Figure 1.1) of the research, which is detailed in Chapters 4, 5, and 6, and were tested among various FFE stakeholders (Objective 3). Through the use of a rapid prototyping approach, improvements to the VR applications were made according to the inputs from various FFE stakeholders. This method made it possible for all the stakeholders to input their requirements while the researcher presented the evolution and outcome of the design. The virtual environment was developed for both VR applications using the BIM authoring tool Autodesk Revit, and the interaction and distributed functionality were enabled using the Unity3D game engine. Unity 3D facilitated the use of a primary, scripting, application programming interface (API) in object-oriented programming (OOP) language, C-sharp (C#), for the development of interactive and distributed functionality.

Objective 3: Test the VR applications in various FFE user scenarios and workflows to ascertain utility and usefulness as well as challenges in implementation.

The third objective (Chapters 4, 5 and 6) of this research was to test the utility and usefulness as well as to identify the challenges associated with implementing the developed VR applications in the workflow of FFE (phase two; Figure 1.1). The VR applications were tested in two segments of the FFE sector: a) the construction supply chains FFE design communications, which is detailed in Chapters 4 and 5, and b) the retail of FFE products to construction stakeholders which is detailed in Chapter 6.

The results of testing the interactive VR application (Chapter 4) showed that:

- All the stakeholders considered that the interactive VR application can improve efficiency, design coordination and productivity significantly (Section 4.7.1).
- FFE design tasks require significantly less time compared with traditional methods of design communication used in the FFE sector (2D paper and 2D digital) (Section 4.7.1).
- Design communication using interactive VR applications encouraged the stakeholders to try various design combinations easier and much faster than traditional methods (Section 4.7.1).
- Interactive VR applications offered extreme flexibility in choosing furniture based on its texture, colour and aesthetics as well as based on the interior space and colour of the rooms, which was impossible when done through conventional methods (Section 4.7.1).
- FFE stakeholders had a higher level of satisfaction with the design they proposed compared with the 2D-based design proposal (Section 4.7.2).
- Spatial perception offered by the interactive VR application assisted in choosing a more efficient FFE design compared with 2D-based methods (Section 4.7.2).
- Stakeholders considered cost, skill requirement and mobility as well as the weight of the HMD to be challenges that can restrain the adoption of a similar application (Section 4.7.2).

The results of testing COFFEE (Chapter 5) for use by FFE in the construction sector showed that:

- COFFEE has a high usability index between good and excellent (Section 5.6.3).
- COFFEE has a high sense of physical space, engagement and ecological validity as well as very low negative effects (Section 5.6.4).
- Stakeholders considered COFFEE to be a highly useful, multi-user, VR platform, which is a novel, innovative and productive tool for application by FFE (Section 5.6.5).
- Stakeholders considered cost (associated with hardware, software and training), skill shortage and inter-operability issues to be major challenges in implementing applications such as COFFEE (Section 5.6.5).
- Immersive communication offered by COFFEE is highly beneficial for stakeholder engagement and decision-making (Section 5.6.5).
- The usability of immersive communication and collaboration tools, such as COFFEE, can be affected by the negative effects caused by the VR environment (Section 5.6.5).
- Perceived presence factors: a) sense of space, b) engagement and c) ecological validity, have no effect on the usability of COFFEE (Section 5.6.5).
- COFFEE was identified as being appropriate for participatory design, particularly when stakeholders involved are elderly and vulnerable (Section 5.6.5).

The results of testing the DVSE (Chapter 6) for use by FFE in the retail segment of the FFE sector showed that:

- All the stakeholders in the retail segment of the FFE sector considered DVSE to be practical, helpful, and relevant to the retail segment which can save costs (Section 6.6).
- All stakeholders considered co-presence as a critical engagement factor that delivers a “sense of being” in the virtual environment (Section 6.6).
- The multi-user interactivity offered by DVSE had a significant impact on the stakeholders’ responses and all stakeholders considered the application to be simple to use and very responsive (Section 6.6).
- The general attitude of the retail stakeholders of FFE towards DVSE was that it was great, innovative, efficient, novel and productive (Section 6.6).
- The retail stakeholders considered DVSE to be worth recommending and expressed high intention to adopt it (Section 6.6).
- Stakeholders also raised concerns about the cost of hardware software and virtual environment development (Section 6.6).

Objective 4: Validate the industry-wide usefulness of the developed VR applications and examine their effectiveness, focusing on challenges and benefits that affect/facilitate the stakeholders’ intentions to adopt VR applications for use in FFE.

The fourth objective (phase three, Figure 1.1) of this research was to validate the industry-wide usefulness of the developed interactive and distributed VR applications and to examine their effectiveness with a focus on challenges and benefits that affect/facilitate the stakeholders’ intentions to adopt VR applications for use in FFE, as detailed in Chapter 7. To achieve this objective, the factors which affect/facilitate VR adoption in the FFE sector were identified from the literature review (Chapters 2 and 3, Objective 1) and from testing the developed VR applications (Chapters 4, 5, and 6, Objective 3) that were carried out among FFE stakeholders. To obtain the opinions of the FFE stakeholders, a survey questionnaire was administered to n = 117 FFE stakeholders. A total of 32 challenges and 25 benefits were identified, which were categorised further into components and ranked based on their mean values. A total of five categories of challenges and four categories of benefits were identified. To determine the relationship of these components with the intention of FFE stakeholders to adopt VR technology, a Kruskal-Wallis ANOVA test and Spearman's correlation analysis were carried out. The findings from the analysis of the survey results showed that:

- The majority of the FFE stakeholders (57.26%) considered both interactive and distributed VR applications to be extremely useful for the FFE sector (Section 7.4.3).
- Distributed and interactive VR applications were considered by 35.04% and 31.62% of stakeholders, respectively, to be very useful for FFE design communication and collaboration (Section 7.4.3).
- A high intention to adopt similar VR applications for design communication and coordination was indicated by 50.4% of the FFE stakeholders, out of which most of the stakeholders were architects and interior designers (Section 7.4.3).
- Stakeholders considered the perceived cost to be the topmost challenge, followed by (in order) skill shortage, immature technology, lack of drivers, privacy and safety and other factors that can affect the intention to adopt similar VR applications in the FFE sector (Section 7.4.4.3.1).

- Stakeholders also considered enhanced user experience, facilitating conditions, and productivity and efficiency (in order) to be other factors that can facilitate the adoption of similar VR applications in the FFE sector (Section 7.4.4.3.2).
- Stakeholders considered improved design communication to be the topmost benefit of VR (Table 8).
- Productivity and efficiency were identified as the only factors that can drive the FFE stakeholders' intention to adopt applications similar to those developed for this research (Section 7.4.4.3.2).

Objective 5: Provide conclusions and recommendations for practice as well as future research.

The final objective of this research is discussed in this chapter under Sections 9.6 and 9.7.

9.3. Contribution to knowledge

I. **Establishment of the current state of the art of immersive technology in the architecture and construction industry and, in particular, the FFE sector**

Thus far, no research has considered the key challenges and benefits associated with the application of immersive technology in the AEC industry, particularly in the FFE sector, with aggregation of findings and knowledge. Despite the enthusiasm and excitement surrounding the application of immersive technology in the FFE sector, there is a substantial gap between the technology that is readily available and the technology that is needed to realise the full potential of immersive technology systems envisioned in various domains of application in the FFE sector. A substantially improved system is imperative for any technology, such as immersive technology, to be truly successful and widely adaptable throughout the industry. This research contributes to the body of knowledge by evaluating the current state-of-the-art immersive technology in the AEC industry, particularly in the FFE sector, systematically to understand the challenges and benefits associated with the adoption of immersive technology in practice and to suggest how future objectives in this area might be pursued.

II. **Identification of the knowledge gaps in the existing VR applications used in the FFE sector**

Three key gaps in the VR applications used in the FFE sector were identified in this research. Evidence suggests that the current state of VR application in the FFE sector lacks three critical advancements, namely: BIM-data interaction (interaction with the meta-data associated with the FFE elements), human-building interaction (interaction of stakeholders with FFE elements in the virtual environment) and human-human interactions (multi-user interaction), which are essential for effective design communication and co-ordination in the FFE sector.

III. **Proposal of a novel methodology for the development and application of an interactive virtual environment for design communication in the FFE sector**

One of the key gaps identified in the current state-of-the-art VR applications used in the FFE sector is the inability to interact with the BIM meta-data and with the FFE elements to manipulate the properties and types. A novel methodology was purposed in this study for the development and application of an interactive virtual environment and the utilisation of a hybrid user interface that alleviates the limitations of a diegetic and non-diegetic interface. The interactive VR application developed for this research, and the proposed approach, provide opportunities for enhanced interpretation of design intent in FFE as well as efficiency in design selection and coordination tasks when compared with conventional 2D methods of communication. This provides a step-change in the way furniture design is communicated and coordinated through an immersive virtual experience. The issue of impact on design coordination has not been addressed in previous studies, instead, the focus has been on marketing and sales.

IV. **Proposal of a novel methodology for the development and application of distributed virtual collaborative environment for use in the FFE sector.**

Another critical gap identified in this research is the inability of the current VR applications in the FFE sector to support distributed (multi-user) asynchronous collaboration where stakeholders can interact, communicate and appraise designs collaboratively in real-time and immersive, while at different geographical locations. This shortcoming of the virtual environment was addressed in this research, enabling concurrent multi-users to interact, communicate and collaborate virtually during design decision-making in the FFE sector. Furthermore, the interoperability issues between the BIM authoring tool (Revit) and the Unity 3D game engine were addressed in this research by proposing a framework for the utilisation of Unity Reflect for streaming the BIM to VR workflow, together with methods of achieving a high-fidelity virtual environment. Furthermore, a contribution to knowledge was made in this research by developing and testing a virtual FFE showroom (Chapter 6) that will allow FFE consumers to shop remotely in a fully immersive and interactive, virtual environment, minimising the risk of physical contact but, at the same time, delivering a rich, meaningful and compelling shopping experience that enables them to make a well-informed and collaborative purchase decision without visiting the physical store.

V. **Development of a framework to integrate the distributed VR and SCRUM for lean construction**

One of the main challenges that FFE stakeholders face while designing a space is to account for the unforeseeable issues, risks and stakeholder requirements iteratively. For a sector such as FFE that operates on narrow profit margins and tight project schedules, the consequences of these unforeseeable issues can have a huge impact on the quality and sustainability of the sector. Even though the SCRUM method has been used widely in the construction industry, together with BIM, no attempt has been made in studies to integrate SCRUM with the distributed VR platform. In this research, a framework was proposed that integrates SCRUM, which is one of the agile project management methods, with the distributed VR application for lean construction.

VI. **Identification of factors affecting/facilitating the adoption of VR in the FFE sector and establishing their relationship with the intention of FFE stakeholders to adopt VR in practice.**

Despite the UK Government's investments (£72 million) and promotion of adopting VR technology in the AEC industry, being low technology-oriented, the FFE sector has fallen behind in embracing VR. This could be attributed to a myriad of complex and inter-related factors that are very difficult to understand and, consequently, implementation of any mitigation plans cannot be devised. In this research, these factors, namely benefits that facilitate and challenges that affect the adoption of VR in the context of FFE were identified and their relationships with the intention of FFE stakeholders to adopt VR in the practice were established. While attempts have been made in some existing studies to identify the challenges and benefits of implementing VR in the AEC industry, no studies had been undertaken thus far to consider how these factors will affect/facilitate the implementation of VR in the FFE sector and how these factors can influence the intention of FFE stakeholders to adopt VR. A valuable indication of which factors to consider is provided in this research for FFE practitioners to devise mitigation plans to streamline VR adoption.

9.4. Practical contribution

The VR applications developed for this research will be highly beneficial for the FFE sector, as is evident from the industry-wide response in which the VR applications were rated to be extremely useful. A streamlined approach was proposed in this research through the development and testing of a novel, collaborative, BIM-based interactive and distributed VR application for the AEC industry generally, and the FFE sector specifically. The results of this research provide meaningful insights for guiding decisions in the development of interactive and distributed VR applications for the FFE sector. The distributed VR application proposed in this study was demonstrated to have a useability rating between good and excellent. This suggests that stakeholders considered the application easy to use and robust, which is critical for applications such as COFFEE. The development methodology proposed in this study will be particularly useful for the practitioner who designs BIM-based interactive and distributed VR applications for use in the FFE sector. Existing studies that demonstrate the integration of BIM and immersive VR indicate that the development of BIM-based VR applications is challenging, cumbersome and time-consuming because they require multiple iterations and lack a synchronised flow of information. A more streamlined approach is proposed in the present study towards integrating BIM and distributed virtual environments with a synchronised flow of information. The system framework and the findings in this research can be applied not only to FFE design decision-making in the construction sector but also in the virtual commerce aspect of the FFE industry. This will assist the FFE suppliers in switching from physical stores to virtual stores, providing an opportunity to display a vast variety of virtual products without having to invest in the warehouse space and products and focus more on experience-based marketing. Furthermore, the relevance of such a system for the consumers cannot be over-emphasised considering the dynamic purchasing behaviour of the consumers as well as the unwillingness of clients to explore vast shop-floor areas to explore the variants of FFE products that are put on display.

9.5. Research limitations

Despite the relevance of the findings of the research, the following limitations are acknowledged.

- To maintain a pre-determined threshold of quality for the literature reviewed in Chapters 2 and 3, only rigorously peer-reviewed journals were considered. Book chapters or non-international journals were excluded, thus satisfying the best-evidence principle proposed by Slavin (1986). The non-inclusion of grey literature resulting in publication bias might be considered to be a limitation of the literature review, but the rationale was solely a trade-off between selecting high-quality literature and the inherent risk of broadening the information bias that must be anticipated when a study of doubtful reliability is included.
- The research was cross-sectional in nature which provides a view of a particular point in time. Since VR and associated technologies are undergoing rapid evolutions with the recent advancement in technology, some of the findings from this research might not have relevance in the future. For example, some of the challenges, such as cost associated with hardware and software, interoperability issues identified during the testing (phase two) and validation (phase three) of the two VR applications might not have relevance in the future.

With the advancements in the chip revolution and ICT, modern-day VR hardware is becoming much cheaper and more affordable. Also, cross-platform game-engine vendors, such as Unity3D, have turned their attention toward the AEC industry to provide middle-ware plugins that work with BIM authoring tools such as Autodesk Revit to streamline the BIM-VR workflow and eliminate inter-operability issues that existed earlier. Thus, it is necessary to assess these factors periodically.

- Although the stakeholders evaluated both VR applications as being extremely useful during the validation, a few stakeholders also made suggestions for improving the VR applications such as virtual environment development targeting low-cost HMDs. These comments are addressed during the industry-wide deployment in Section 9.7.

9.6. Conclusions

From an extensive review of literature and state of the art, it was identified that no studies had been undertaken to investigate the effectiveness of VR as a communication tool in FFE workflow. There is a strong concern in the FFE sector that the current utilisation of VR applications compromises the full potential of VR because the environmental representation is focused predominantly on the visual modality, regardless of other endless possibilities such as utilising attached meta-data to interact and manipulate the information-rich BIM model and improve the decision-making process through remote collaboration. This poses an additional challenge as the knowledge and research about what constitutes an efficient and effective visualisation, collaboration and communication tool lags behind the rapidly evolving technology. Therefore, a novel methodology was proposed in this study for the development and testing of interactive and distributed virtual environments for immersive communication between the FFE sector and its construction project stakeholders.

Pre-conditions for the successful implementation of the developed immersive applications were evaluated further in the study through experimentation. The novelty of this research lies in the development, testing and validation of the interactive and distributed VR applications that can assist FFE stakeholders when communicating with their stakeholders. In doing so, this study bridges the gap between the current state-of-the-art application of VR in the FFE sector specifically and the AEC industry generally.

9.7. Recommendations

Based on the findings of this research, recommendations for FFE in the construction sector and retail sectors, as well as recommendations for future research are proposed.

9.7.1. Recommendations for FFE in the construction sector

The implications of the research findings for the practices within the FFE sectors operation in the construction supply chain can be summarised as follows:

- At the time of this research, major interoperability issues existed between BIM authoring tools and immersive content creator tools. The content for this research was created using various middle-ware tools and several iterations to achieve interactivity and multi-user functionality. While the adoption of BIM in the FFE sector is gaining momentum, the implementation of similar VR applications without addressing the interoperability issues could adversely affect the workflow.
- Additional training might be required for FFE content developers to create an interactive

VR experience, which was omitted from the analysis of this research. Therefore, additional investments might be required, including training needs throughout the current workflow for the organisational-wide adoption of this system. Moreover, the entire system was built to achieve a high-fidelity VR "ecosystem" that requires high-end processors and dedicated space that could add to the investments.

- With the introduction of virtual reality-based collaborative environments, such as Metaverse, the transition to immersive collaboration will be easier. However, it is necessary for some of the existing limitations, such as interoperability between BIM authoring tools and virtual environment development packages, to be considered and more studies are needed to explore the possibilities of utilising Metaverse as a design communication and coordination tool. It is noted that the distributed VR developed for Experiment 2 (Chapter 5) of this research shares close functional similarities with Metaverse, but it is necessary to carry out more studies in this area to understand whether these two applications share common limitations and ways of alleviating those limitations for a smoother adoption of these technologies.
- Even though the low-cost, standalone HMDs are available that enable enhanced user mobility whilst in a virtual environment, a limiting factor associated with these devices is their capability to store and load large and complex BIM models, as well as the insufficient battery capability. Industry practices targeting their VR development at these types of HMDs should ensure that the model polygon count is restricted to being within the recommended limits specified by the manufacturer. At the time of this research, minimising the polygon count was impossible within the BIM authoring tool (Autodesk Revit), hence the integration of additional modelling tools into the workflow was essential.

9.7.2. Recommendation for FFE in the retail sector

The implication of the research findings for the retail segment of the FFE sector is outlined below:

- Unlike the construction segment of the FFE sector, inter-operability issues were not a major concern for the retail segment of the FFE sector because non-parametric 3D modelling tools, such as Blender, can minimise the need for multiple iterations before the virtual environment is VR ready. However, the requirements of a skilled workforce, additional space, hardware and software requirements, as well as the cost associated with these additional requirements, must be taken into consideration. Since the retail segment of the FFE sector does not operate on project-specific designs, the retail segment can create a virtual showroom that incorporates all the FFE products that will enable the construction stakeholder (and other customers) to have virtual showroom walk-throughs. The virtual environment development of these showrooms will be a one-time development and will only require minor updates as new FFE products are added to the product range. This opportunity could reduce the requirement for employing a dedicated workforce solely for VR development.
- Current VR HMDs are also not sufficiently comfortable for prolonged use because of the weight of the device and user experience within the virtual environment. These factors can discourage the uptake of this technology.

9.7.3. Recommendation for future research

The recommendations for future studies are discussed below.

- It is evident from this research that VR is a viable tool for design communication and coordination in the FFE sector. However, the impact of the various sensory modalities on improving the efficiency of the construction task in the virtual environment is still unclear and requires further investigation. It was identified in this research that multi-sensory requirement was considered to be a challenge in only 9 out of 51 literature sources (Chapter 3). It is noted that, apart from the usual sensory cues (visual and auditory), very few or no sources were focused on incorporating other multi-modalities such as haptic and olfactory senses.
- In addition to this, measuring the success of the developed application must be validated by researchers from both academia and industry. It is assumed that the VR system will be assessed by the FFE sector, based on the contents, features and value for money. Therefore, any future research should be focused on developing VR systems that are capable of synchronising project information, preferably in a real-time, user-friendly interface that can be diffused easily into the workflow of the FFE sector and, from a value perspective, can give the user a return on investment in a shorter period.
- In this literature review, it was found that, in the present state of ImT, most of the system development was at a prototype or trial stage and, therefore, lacked the above attributes. However, since technology is in a phase of rapid evolution, it is highly recommended that industry partners monitor these developments closely and incorporate those which could bring value. For future development, the researchers will investigate the integration of COFFEE with low-cost HMDs, such as Gear VR, focusing on widening the accessibility of the application to all levels of stakeholders. However, this process might require limiting certain functionalities and visual quality of COFFEE for a smooth multi-user experience.

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Appendices

Appendix A: Thesis author's articles in-preparation / published which are not related to this study but developed during the research period as a result of research training.

[1]. Mahamadu, A., Okeke, U., **Prabhakaran, A.,** Booth, C. A., and Olomolaiye, P. (2022). I spy with my little eye: Improving user involvement in elderly care facility design through virtual reality. In C. Gorse, L. Scott, C. Booth, and M. Dastbaz (Eds.), *Climate Emergency – Managing, Building, and Delivering the Sustainable Development Goals* (385-394). Springer. https://doi.org/10.1007/978-3-030-79450-7_29.

[2]. Mahamadu, A., **Prabhakaran, A.,** Clark, K., Dziekonski, K., Okeke, U., Zhang, W., Aigbavboa, C. O. (2021). The application of eye-tracking technology in architecture engineering and construction industry: A systematic review. In N. Dawood, F. Pour Rahimian, and M. Sheikhkhoshkar (Eds.), *Proceedings of the 21st International Conference on Construction Applications of Virtual Reality* (56-64)

[3]. **Prabhakaran, A.,** Mahamadu, A. M., Mahdjoubi, L., Andric, J., Manu, P., and Mzyece, D. (2021). An investigation into macro-BIM maturity and its impacts: A comparison of Qatar and the United Kingdom. *Architectural Engineering and Design Management*, 17(5-6), 496-515. https://doi.org/10.1080/17452007.2021.1923454.

[4]. Mahamadu, A., **Prabhakaran, A.,** Manu, P., Pérez, D., and Szóstak, M. (2022-In Press) Safety Risk Factors in The Use of Construction Robots. In: Manu, P., Shang, Gao., Bartolo, P. Francis, V., and Sawhney, A., eds. (In press) *Handbook of Construction Safety, Health and Well-being in the Industry 4.0 Era*. London: Routledge

[5]. Archila, H., Lashely, R., **Prabhakaran, A.,** and Mispo, A. (2022- Accepted). Smartifying construction for circular and zero carbon biobased building (SmartBioC*): Sustainable Ecological Engineering Design for Society (SEEDS).*

[6]. Booth, C.A., Horry, R., Isaac, C., Mahamadu, A-M., Manu, P., Awuah, K.G.B., Aboagye-Nimo, E., Georgakis, P. and **Prabhakaran, A.** (2022-Accepted). Earthship buildings: Stakeholder opinion for their contribution towards sustainable alternative housing in the UK: *Management Procurement and Law*

[7]. Booth, C.A., Rasheed, S., Mahamadu, A-M., Horry, R., Abbey, S., Manu, P., Awuah, K.G.B., Aboagye-Nimo, E., Georgakis, P. and **Prabhakaran, A.** (Under Review). A Phenomenological Inquiry of Building and Living in European Earthship Homes: *Buildings*

[8]. Ball, S., Booth, C., **Prabhakaran, A.,** Mahamadu, A-M., Glass, J. (Under Review). Responsible sourcing in the architecture, engineering and construction (AEC) sector of the UK: *Engineering Construction and Architectural Management*

[9]. Ball, S., Booth, C., **Prabhakaran, A.,** Mahamadu, A-M., Glass, J. (2022-Accepted). A systematic review of responsible sourcing literature across the architecture, engineering and construction (AEC) sector: A systematic literature review: *Sustainable Ecological Engineering Design for Society (SEEDS).*

[10]. Mahamadu, A., **Prabhakaran, A.,** Booth, C.A., and Dziekonski, K. (2022 Accepted). Measuring Visual Attention using Virtual-Reality and Computer-Vision for Construction Safety: *Sustainable Ecological Engineering Design for Society (SEEDS).*

[11]. Cann, S., Mahamadu, A., **Prabhakaran, A.,** Dziekonski, K., and Joseph, R. (Under Review) An Approach for Semi-Automated Data Quality Assurance within BIM Models. *Engineering Management in Production and Services*

[12]. Arvanitis, L., Mahamadu, A-M., Manu, P., Kissi, E., Al-Tarazi, D., **Prabhakaran, A.,** Booth, C. (Under review) A Quantitative Enquiry into BIM Maturity and its Influence on Implementation Challenges. *Smart and Sustainable Built Environment*

❖ Awards for articles published

- *Smart and Sustainable Digital Innovation Award: Health Care (2020)* Mahamadu, A., Okeke, U., **Prabhakaran, A.,** Booth, C. A., and Olomolaiye, P. (2022). I spy with my little eye: Improving user involvement in elderly care facility design through virtual reality. In C. Gorse, L. Scott, C. Booth, and M. Dastbaz (Eds.), *Climate Emergency – Managing, Building, and Delivering the Sustainable Development Goals* (385-394). Springer. https://doi.org/10.1007/978-3-030-79450-7_29.