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Abstract

Purpose

The Furniture, Fixture, and Equipment (FFE) sector is well placed to leverage virtual reality (VR) technology for competitive and operational advantages, however, 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.

Design/Methodology/Approach

A sequential exploratory mixed research methodology consisting of three phases was adopted for this study. This included the identification of factors that affect/facilitates the implementation of VR (Challenges and Benefits) using experiments during in-house prototyping of VR applications, a rigorous literature review and a questionnaire survey to solicit FFE Stakeholder's (n=117) opinion on the utility and usefulness of the proposed applications and to the understand factors that facilitate and inhibit their implementation in FFE's context, particularly as a design communication and coordination tool.

Findings

The findings of this study revealed that distributed and single-user 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.*

Originality/Value

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

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 & Asikainen, 2001; Prabhakaran et *al.*, 2021). Thus, aesthetics plays a vital role compared with other criteria such as cost and functionality (Creusen & 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.

2. Literature Review

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 & 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 & Khali, 2018). These levels can be divided generally into three categories (Figure 1): *a*) Passive *b*) Exploratory, and *c*) Immersive VR (Pimentel & Teixeira, 1993).

Figure 1

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 & Teixeira, 1993). However, "immersive VR is the classic stage of VR, users can fully interact with the VE, simulating 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 2 presents the Reality-Virtuality continuum (Milgram & Colquhoun, 1999) which ranges from entirely virtual to entirely real thus entailing all possibilities in between.

Figure 2

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 the 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, were every individual user share the same perspective, movement and interaction as noted by (Spaeth & Khali, 2018; de Freitas *et al.,* 2022). 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 5.

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 & 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 & Liu, 2018) facility management (Shi, Du, & 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.

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, sections 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 & Eggert, 2013), they lack depth and spatial perception which makes the process less intuitive for the stakeholders (Carrasco & 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 & 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.

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 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.

Figure 3

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.

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 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 1

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.

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.

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 2 and 3 show the lists of factors identified.

3.4.1. *Experiment 1-Interactive Single User 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 4

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 4 presents the first-person view of a stakeholder interacting with the FFE element to achieve an optimised design.

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 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 5

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 6 presents the first-person view of one of the stakeholders involved in collaborative decision making, where all stakeholders are represented using avatars.

Figure 6

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 to 2019 (inclusive) were selected using inclusion-exclusion criteria.

Figure 7

A *four-stage* approach (Figure 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.

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

Tables 2 and 3

4. Results and Discussion

4.1. Background of Respondents

As presented in Table 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.

4.2. Characteristics of Respondents' Organisations

The characteristics of the respondents' organisation (Table 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 1and 9, followed by 17.10% which had more than 250 employees.

Table 4

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.

Figure 8

Figure 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 9) such as 2D paper-based, 2D digital, 3D BIM etc. while selecting furniture and interior fixtures for the types of projects they undertook.

Figure 9

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 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). 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.

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 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 10 illustrates the respondents' perceptions about the usefulness of both VR applications for FFE's design communication and collaboration.

Table 5 and Figure 10

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 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. 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

6) was performed using Dunn's procedure (1964) with a Bonferroni correction for multiple comparisons. 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 6

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 & 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 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.

4.4. Factors Affecting and Facilitating VR Implementation in FFE Sector

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) indicated that all the components had a CA value higher than 0.70 indicating a high internal consistency.

4.4.2. Ranking and Categorisation of VR Implementation Factors

The VR implementation factors identified were examined using descriptive statistics (Tables 7 and 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 and 8 show the ranking of each factor based on its mean score. To simplify the complexity of the large number of data sets each of the VR implementation factors was categorised into components (Table 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 has been examined in detail.

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

4.4.3.1. Challenges affecting VR Implementation in the FFE Sector

Based on the respondents' perceptions (Table 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.

Table 7

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 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 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. 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 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 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.

4.4.3.2. Benefits Facilitating VR Implementation in FFE Sector

Respondents considered *improved design communication* to be the topmost benefit (Table 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.

Table 8

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 copresence offered by distributed VR.

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.

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

Abstract

Purpose

The Furniture, Fixture, and Equipment (FFE) sector is well placed to leverage virtual reality (VR) technology for competitive and operational advantages, however, 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.

Design/Methodology/Approach

A sequential exploratory mixed research methodology consisting of three phases was adopted for this study. This included the identification of factors that affect/facilitates the implementation of VR (Challenges and Benefits) using experiments during in-house prototyping of VR applications, a rigorous literature review and a questionnaire survey to solicit FFE Stakeholder's (n=117) opinion on the utility and usefulness of the proposed applications and to the understand factors that facilitate and inhibit their implementation in FFE's context, particularly as a design communication and coordination tool.

Findings

The findings of this study revealed that distributed and single-user 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.*

Originality/Value

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

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 & Asikainen, 2001; Prabhakaran et *al.*, 2021). Thus, aesthetics plays a vital role compared with other criteria such as cost and functionality (Creusen & 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.

2. Literature Review

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 & 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 & Khali, 2018). These levels can be divided generally into three categories (Figure 1): *a*) Passive *b*) Exploratory, and *c*) Immersive VR (Pimentel & Teixeira, 1993).

Figure 1

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 & Teixeira, 1993). However, "immersive VR is the classic stage of VR, users can fully interact with the VE, simulating 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 2 presents the Reality-Virtuality continuum (Milgram & Colquhoun, 1999) which ranges from entirely virtual to entirely real thus entailing all possibilities in between.

Figure 2

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 the 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, were every individual user share the same perspective, movement and interaction as noted by (Spaeth & Khali, 2018; de Freitas *et al.,* 2022). 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 5.

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 & 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 & Liu, 2018) facility management (Shi, Du, & 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.

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, sections 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 & Eggert, 2013), they lack depth and spatial perception which makes the process less intuitive for the stakeholders (Carrasco & 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 & 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.

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 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.

Figure 3

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.

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 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 1

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.

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.

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 2 and 3 show the lists of factors identified.

3.4.1. *Experiment 1-Interactive Single User 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 4

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 4 presents the first-person view of a stakeholder interacting with the FFE element to achieve an optimised design.

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 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 5

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 6 presents the first-person view of one of the stakeholders involved in collaborative decision making, where all stakeholders are represented using avatars.

Figure 6

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 to 2019 (inclusive) were selected using inclusion-exclusion criteria.

Figure 7

A *four-stage* approach (Figure 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.

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

Tables 2 and 3

4. Results and Discussion

4.1. Background of Respondents

As presented in Table 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.

4.2. Characteristics of Respondents' Organisations

The characteristics of the respondents' organisation (Table 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 1and 9, followed by 17.10% which had more than 250 employees.

Table 4

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.

Figure 8

Figure 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 9) such as 2D paper-based, 2D digital, 3D BIM etc. while selecting furniture and interior fixtures for the types of projects they undertook.

Figure 9

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 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). 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.

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 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 10 illustrates the respondents' perceptions about the usefulness of both VR applications for FFE's design communication and collaboration.

Table 5 and Figure 10

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 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. 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

6) was performed using Dunn's procedure (1964) with a Bonferroni correction for multiple comparisons. 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 6

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 & 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 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.

4.4. Factors Affecting and Facilitating VR Implementation in FFE Sector

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) indicated that all the components had a CA value higher than 0.70 indicating a high internal consistency.

4.4.2. Ranking and Categorisation of VR Implementation Factors

The VR implementation factors identified were examined using descriptive statistics (Tables 7 and 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 and 8 show the ranking of each factor based on its mean score. To simplify the complexity of the large number of data sets each of the VR implementation factors was categorised into components (Table 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 has been examined in detail.

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

4.4.3.1. Challenges affecting VR Implementation in the FFE Sector

Based on the respondents' perceptions (Table 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.

Table 7

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 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 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. 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 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 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.

4.4.3.2. Benefits Facilitating VR Implementation in FFE Sector

Respondents considered *improved design communication* to be the topmost benefit (Table 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.

Table 8

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 copresence offered by distributed VR.

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.

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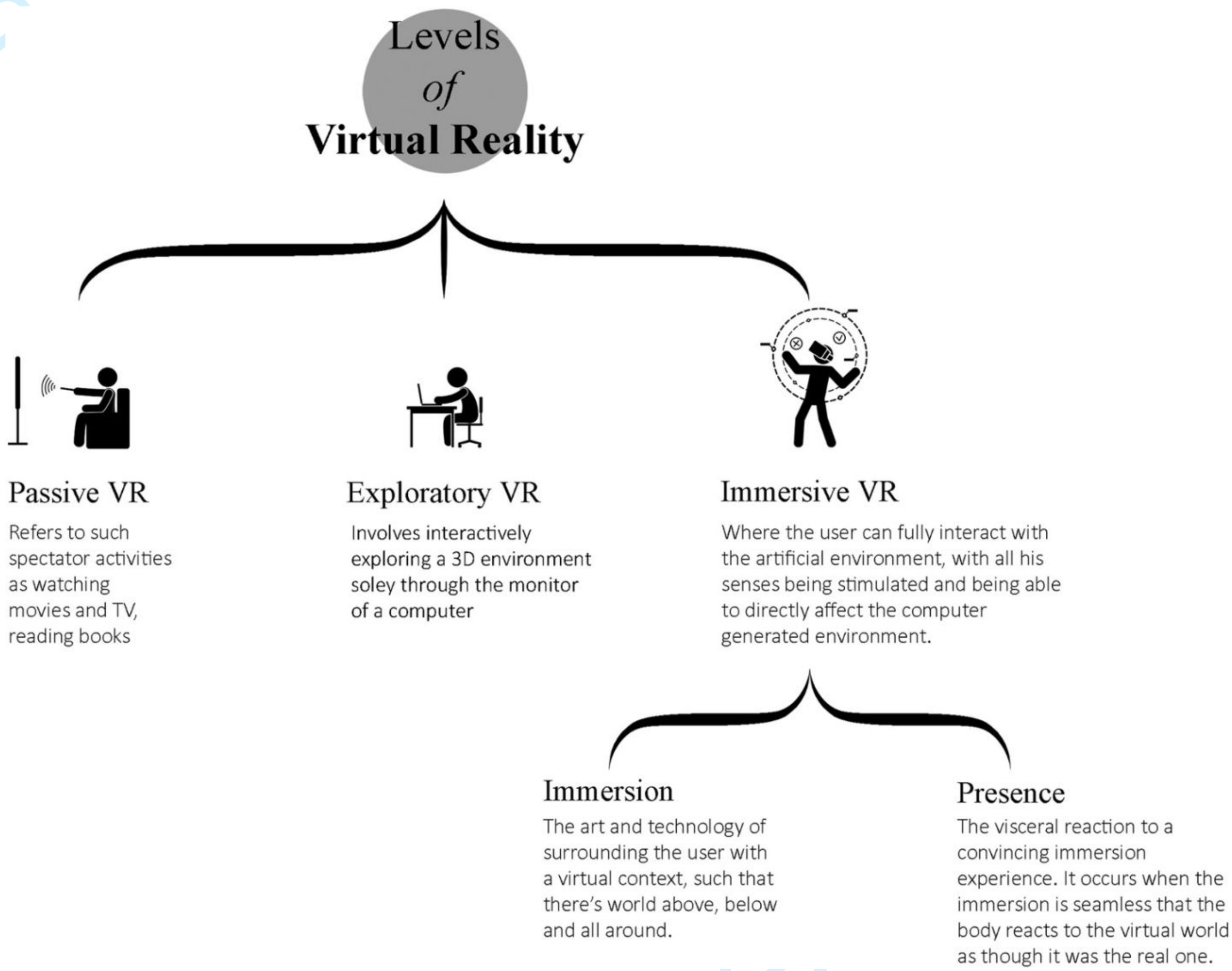

Figure 1: Levels of Virtual Reality (Spaeth & Khali, 2018)

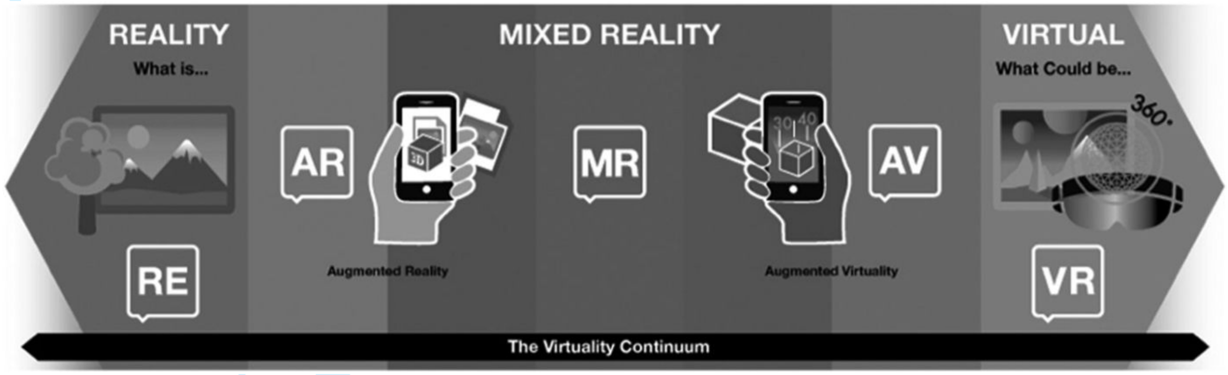

Figure 2: Reality Virtuality Continuum (after Milgram & Colquhoun, 1999)

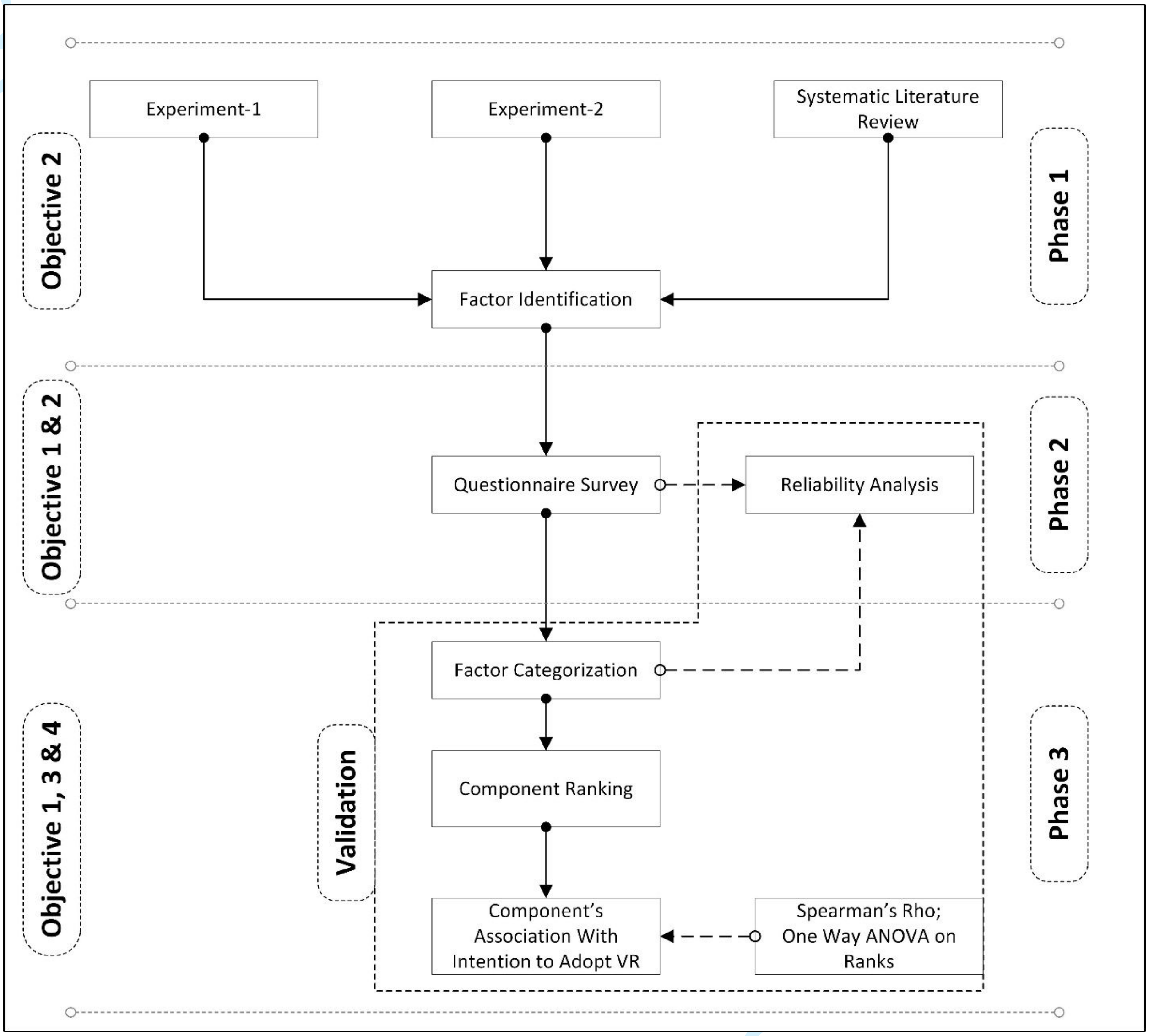

Figure 3: Research Framework

Figure 4: Stakeholder Interacting with FFE elements

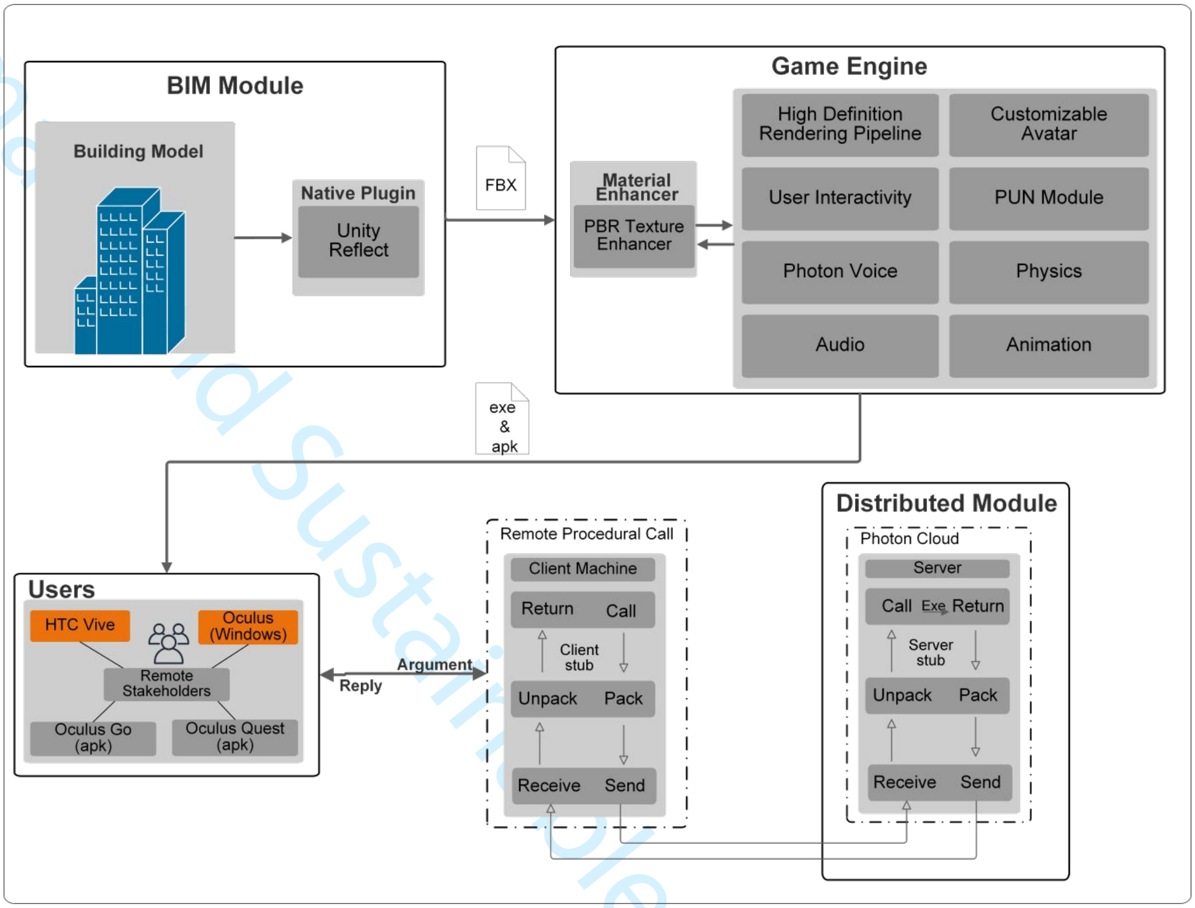

Figure 5: System Architecture

Figure 6: Stakeholders (avatar representation) collaboratively deciding FFE finish (countertop finish).

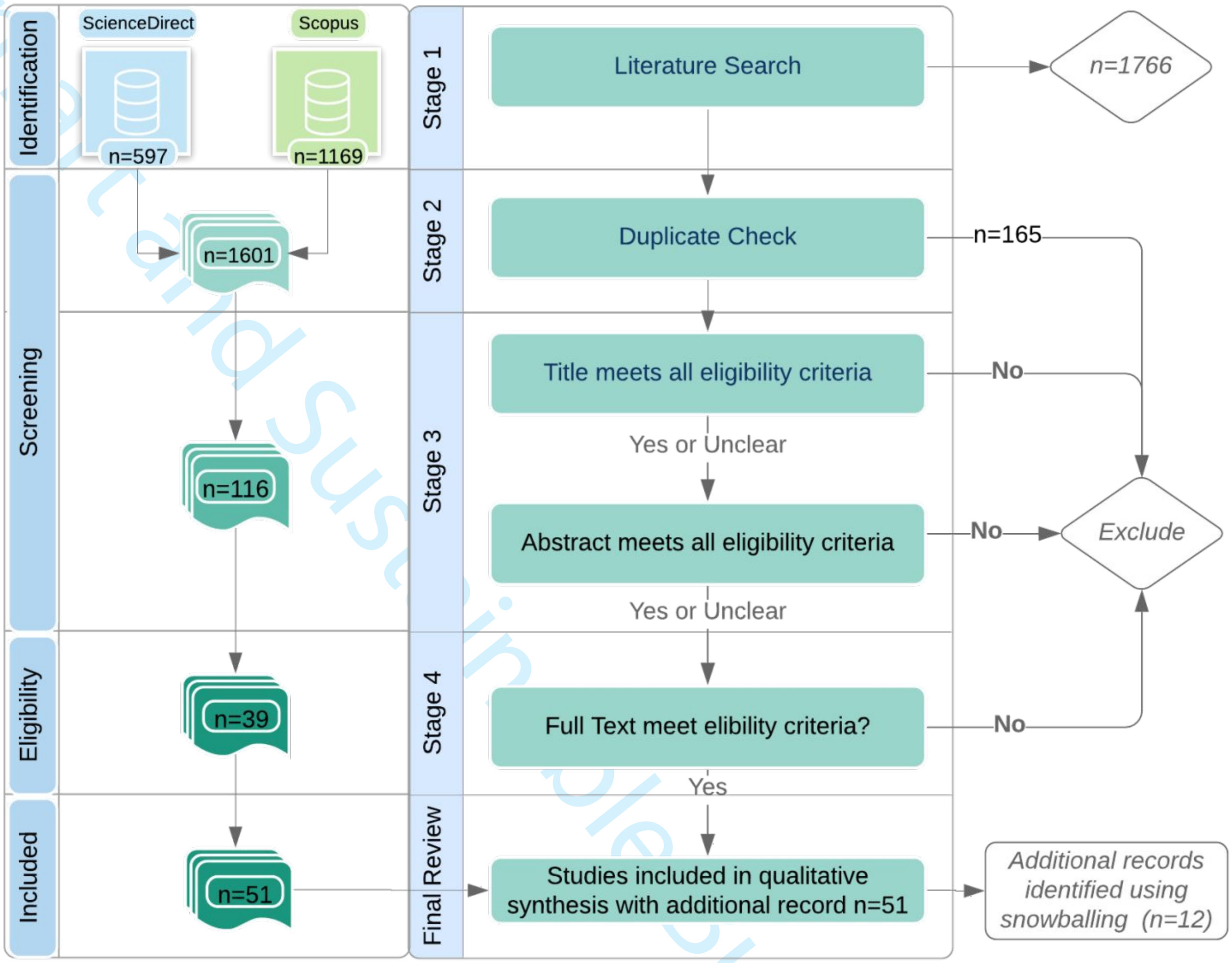

Figure 7: Literature selection process

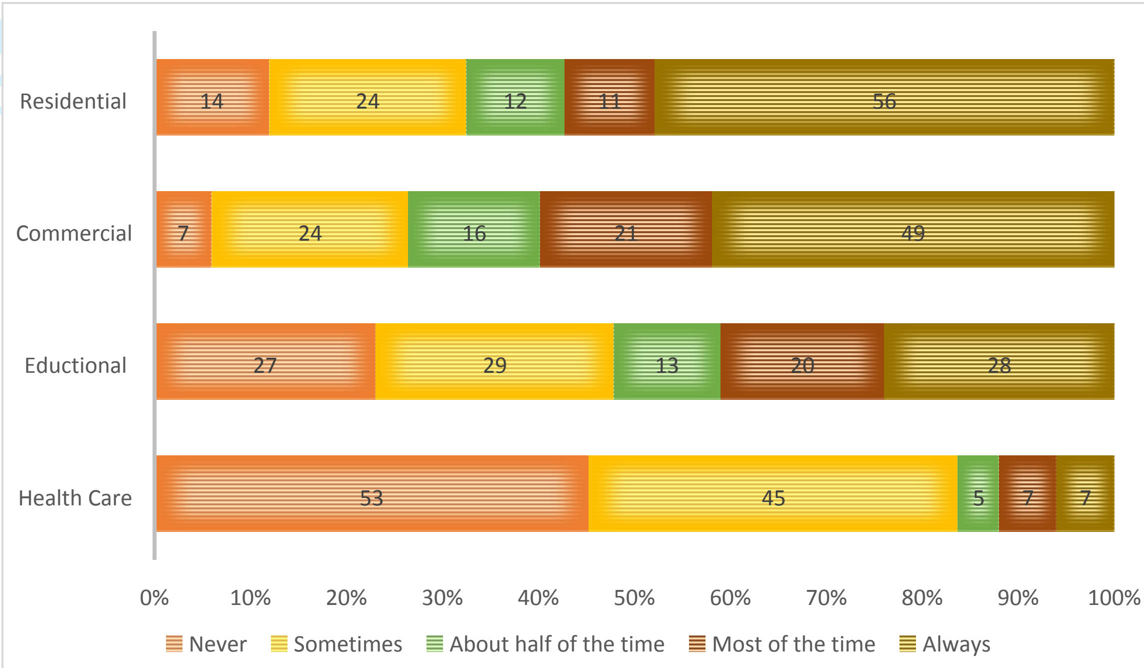

Figure 8: Type of Projects Respondents' Organisation Undertake

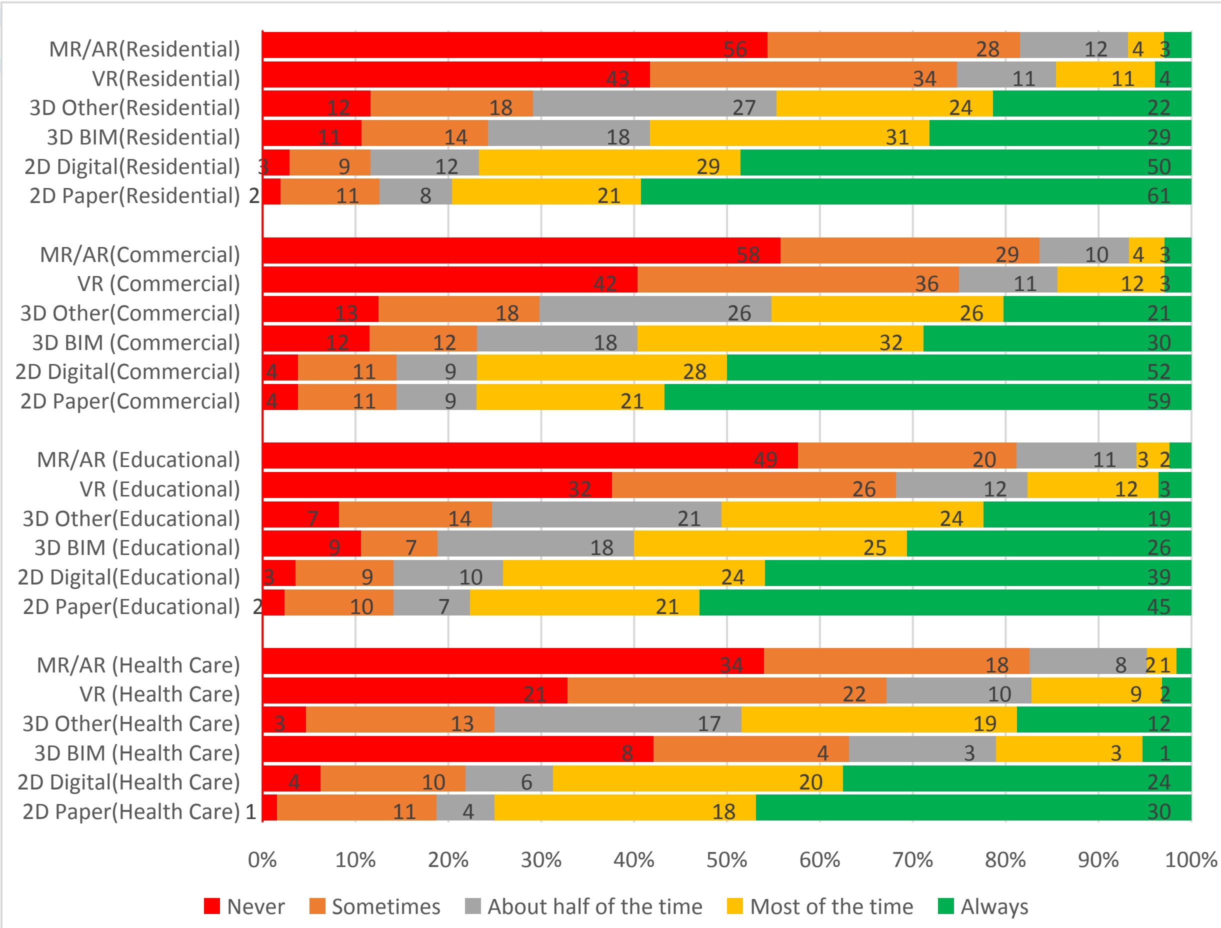

Figure 9: Design Communication Methods Used on Different Projects

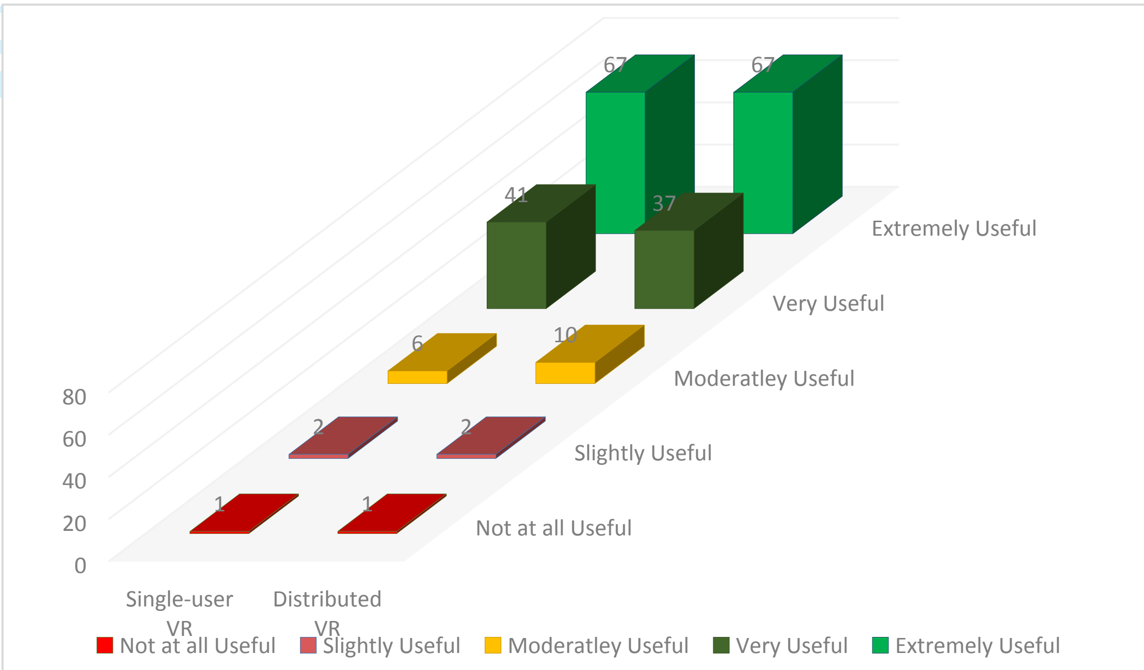

Figure 10: Usefulness of Single-user and Distributed VR Application in FFE Sector

Table 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

Table 2: Benefits Facilitating VR Implementation

Systematic Literature Review	**Label**	**Reference**	**Experiment 1**	**Experiment 2**
Improved visualisation/simulation of design.	B1	(Chalhoub & 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 & Vance, 2017; Bordegoni & Ferrise, 2013)		
Speedy design decision.	B6	(Roupé *et al*., 2016; Zaker & 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 & Coloma, 2018)	√	
Cost-saving.	B12	(Mahamadu *et al*., 2022; Wolfartsberger, 2019; Zaker & Coloma, 2018)		
Improved understanding of design through immersion compared to traditional methods like paper-based design.	B13	(Chalhoub & 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 & 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 & Ayer, 2018)		
Enables early involvement of technical and non-technical stakeholders.	B18	(Chalhoub & Ayer, 2018; Mahamadu *et al*., 2022)	√	√
Identify design-related issues before they occur.	B19	(Chalhoub & Ayer, 2018; Mahamadu *et al*., 2022; Zaker & 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 & 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 3: Challenges Affecting VR Implementation

Systematic Literature Review	**Label**	**Reference**	**Experiment 1**	**Experiment 2**
Costly Hardware and software	C1	(Chalhoub & 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 & Ayer, 2018; Du *et al*., 2018; El Ammari & 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 & Ayer, 2018; Du *et al*., 2018; El Ammari & Hammad, 2019; Wolfartsberger, 2019; Zaker & Coloma, 2018)	√	√
Heavy head-mounted devices.	C7	(Oke & Arowoiya, 2021)	√	
Limited view angle in VR display	C8	(Chalhoub & 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 & 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 & Golparvar-Fard, 2011; Portman *et al*., 2015; Zhang *et al*., 2019)		
Ethical issues such as user privacy, data protection etc.	C15	(El Ammari & 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)	√	
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 & Hammad, 2019; Wolfartsberger, 2019; Zaker & 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 & 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 & 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 & 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)	√	√

Table 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

Table 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
	Low-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

Table 6 Pairwise Comparison

	Levels of Adoption$^{Mean/Median\ Rank}$	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.^{a}
Interactive VR	Non-Adopter$^{37.93}$-Median 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
	Median Adopter$^{50.97}$-High Adopter$^{68.44}$	-17.470	5.687	-3.072	0.002	0.006
Distributed VR	Non-Adopter$^{21.57}$-Median 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
	Median Adopter$^{52.55}$-High Adopter$^{69.02}$	-16.468	5.728	-2.875	0.004	0.012
Intention to Spend	Non-Adopter$^{15.43}$-Median 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
	Median Adopter$^{64.30}$-High Adopter$^{59.58}$	4.719	6.156	0.767	0.443	1.00
Immature Technology	Non-Adopter$^{2.33}$-Median 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
	Median Adopter$^{3.25}$-High Adopter$^{3.66}$	-13.734	6.479	-2.120	0.034	0.045
Perceived Cost	Non-Adopter$^{3.80}$-Median 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
	Median Adopter$^{3.80}$-High Adopter$^{4.20}$	-15.064	6.454	-2.334	0.020	0.046
Skill Shortage	Non-Adopter$^{3.00}$-Median 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
	Median 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

Table 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 & 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 programme/script 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 is 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 limitation, 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, 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 & 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, 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

Table 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