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BIM-based immersive collaborative environment for furniture, fixture and equipment design

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ABSTRACT

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

1. Introduction

In recent years, various segments of the Architecture Engineering and Construction (AEC) industry, including the Furniture Fixture and Equipment (FFE) sector, which is one of the critical segments of interior design has witnessed a steady increase of interest in the use of immersive technologies such as Virtual Reality (VR) aimed at improving the work process. The potential of VR in the AEC industry has been explored in the past by various studies and in particular studies (e.g., [30,86]) have demonstrated the effectiveness of VR during the appraisal of a building's interior design. While many of these studies so far have been focused on understanding the potential of VR during the appraisal of the interior design of a building, various technical limitations exist in the current state of VR that could restrain the full-scale application and adoption of this technology. One of the most critical issues is related to the inability to have a collaborative virtual environment where a group of geographically remote stakeholders can interact, effectively communicate, and appraise designs collaboratively in real-time [61]. This limitation has not been addressed because the development process for such distributed VR applications is complex and the infrastructure requirements for such developments are resource demanding [54]. This has been addressed in this study by proposing a more streamlined approach through the development and testing of a novel collaborative VR tool for the FFE sector named COFFEE. Even though the concept of COFFEE could be applied to wider segments of interior design, the FFE sector which is one of the critical segments of the interior design was chosen for this study to demonstrate the usefulness of COFFEE. The rationale behind choosing the FFE sector for testing the usefulness of COFFEE was because FFE plays a critical role in connecting the built environment with its occupants who spend 90% of their time indoors [23]. The amount of time that occupants spend indoors emphasises the significance of FFE and its effective arrangements in influencing human experience within a built space, which demands a collective decision-making environment. The findings of a study by Saffo et al. [63] suggested that tasks performed in a collaborative virtual environment can yield very high efficiency when compared with single-user virtual environments.

Therefore, in this study it has been proposed that the aforementioned

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

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

2. Immersive technology and design communication in the FFE sector

The process of design communication in the FFE typically involves a linear flow of information among the stakeholders starting from the designer to the end-user/client. Shannon, [69] explained this mode of communication as the theory of linear standard communication process involving encoding and decoding of messages at transmitting and receiving ends, which often lead to potential noise in the communication transmitted. In FFE's context, the designers create a design, which is then encoded into a set of plans which are then communicated among the stakeholders. Until recently, FFE's communication of design relied on traditional tools and methods such as 2D technical drawings, sketches, and pictures resulted in poor stakeholder engagement and a decline in productivity [55] as a result of the noise created at the decoding stage. The poor stakeholder engagement and decline in productivity could be attributed to the fact that not all stakeholders involved in the FFE's design appraisals have similar comprehension capabilities. This difference among the stakeholders has been widely acknowledged since the seminal work by Schön, [68], who points out that the end-user/client and designers occupy an entirely different design world making design communication more challenging. However, recently FFE sector has embraced digital processes, such as Building Information Modelling (BIM) to create data-rich three-dimensional (3D) models to communicate its designs with stakeholders [19]. Although the adoption of BIM has assisted the FFE sector to communicate its design with its stakeholders effectively, the sophistication of the current designs has reached a point where it exceeds the comprehension and interpretation capabilities of some of the critical stakeholders, limiting them from engaging effectively in the design appraisal process [80] because of the so-called "black box effect" that refers to a system that lacks transparency and legibility in communicating with the participants [58].

In recent years, human-computer interfaces, such as VR, have been introduced in an attempt to address the communication and engagement gap in the FFE sector, with aim of offering a reliable extension of BIM for more advanced visualisation as well as communication [59]. Time-saving and the reduction of costly physical prototypes are some of the well-known benefits derived from the application of VR [83]. The opportunity for immersive visualisation offered by VR has a critical role in the FFE sector, as FFE's procurement is often based on three primary criteria- aesthetics, cost and functionality, of which aesthetic merit is the most valued during a design appraisal [85]. Yoon et al. [85] noted that, when the cost and functionality of the FFE alternatives are similar, people tend to choose the option that is more aesthetically appealing. Thus, the traditional means of product presentation offered by the FFE sector using either a two-dimensional (2D) plan or 3D models on a 2D interface are not sufficiently effective for the stakeholders to gauge the aesthetic merits during the design communication. However, the use of VR has offered a step-change in the way the FFE designs are presented to the stakeholders. In a study by Sampaio et al. [64], it was concluded that, compared with the indirect experience offered by 2D presentation mediums like catalogues and sketches, the immersive virtual experience offers better stakeholder perception which is close to direct experience with space. In some studies [50,61] it has been noted that immersive visualisation can increase the stakeholder's information bandwidth thus reducing the time required for effective communication. Oliver, [50] concludes that virtual spatial proximity offered by immersive VR reduces the perceived spatial and temporal distances, thus enriching the perception of richness in effective communication. While much of the studies in the past have focused on developing isolated VR experiences, studies (e.g., [40,50]) highlight the importance of co-presence in the VR which is considered as the antecedent of effective communication among the stakeholders. A study by Schnabel and Kvan, [67] reiterated the importance of co-presence in VR and concludes that design communication in a collaborative, immersive, virtual environment can yield new and meaningful results. In VR assisted design communication, co-presence could only be possible through the development of a collaborative VR system that allows concurrent multi-users to interact, communicate and collaborate during the design-making process.

3. Distributed VR

Nayak and Taylor [49] described a project team as a virtual team, which Chinowsky and Rojas [16] defined in the context of the construction industry as "a group of people with complementary competencies executing simultaneous, collaborative work processes through electronic media without regard to geographic location". Apart from the benefits offered by these virtual teams, the construction literature has noted potential challenges that are faced in virtual project teams such as issues relating to communication, development of trust, and quality control [49]. Furthermore, unlike other sectors of the AEC, FFE's design communication involves stakeholders with both technical and non-technical backgrounds which makes the communication process even more difficult. Distributed VR can provide a possible solution to these challenges in the FFE's communication process. Roehl [60] defines a distributed VR (DVR) as a simulated world that runs on multiple processors that are connected by the internet and the users in the virtual environment can interact remotely and simultaneously in a meaningful way in real-time, sharing the same virtual world. Even though the concept of DVR can be traced back to the early 1990s, recent improvements in hardware, software and high-speed internet connectivity have rendered its application viable and worthwhile [47]. The central concept of DVR is a multi-user virtual environment, where participants can meet, collaborate and interact regardless of their geographic location, which has become one of the most promising uses of VR. Since its first ideation two decades ago, DVR has been lauded as an effective platform that has aided the communication of ideas effectively within a team. Since then, DVR technology has been explored by researchers from various domains.

3.1. Related works

Even though the potential of VR for design communication in the FFE sector has been established in a plethora of studies, there exists a dearth of studies that utilises the application of DVR in the AEC industry generally [54,74] and FFE sector specifically [55]. Some of the most notable applications of DVR for collaborative communication in the AEC industry have been observed in studies by Boton [5]; Tea et al. [74]; Roupé et al. [61]; Du et al. [21] and Prabhakaran et al. [55]. Du et al. [21] and Boton et al. [5] proposed a BIM-based multi-user system for collaborative communication in an immersive virtual environment. In their study, Du et al. [21] and Boton [5] demonstrated that DVR could improve inter-personal interactions and enhance communications in a construction project through co-presence. Similarly, Roupé et al. [61] proposed a collaborative design system for creative and shared design also reiterating the findings of Du et al. [21] and concluding that multi-user immersive VR applications can enhance the stakeholders' understanding of the design and improves their communication and collaboration within the team. The effectiveness of DVR in the FFE sector was proposed by Prabhakaran et al. [55], who compared 2D based design and immersive DVR. Their study also concluded that the sense of being in the virtual environment has a significant effect on the users' performance in completing tasks whilst in the virtual environment. Cumulative evidence from these studies suggests that the use of DVR for collaborative decision-making process can enhance cognition among remote users, aids in better understanding of designs, enables effective participation of all stakeholders, and encourages knowledge sharing.

However, based on an extensive review of the literature, it is evident that gaps in knowledge remain. Firstly, there are very few studies [5,21] which integrate BIM and DVR for design communication and collaboration. The synergy between BIM and DVR is critical for sectors, such as the FFE, which are currently on the path of adopting BIM and other digital technology. Secondly, in existing studies in which the integration of BIM and DVR was demonstrated, it was noted that the development of BIM-based DVR applications is challenging, cumbersome and time-consuming as they require multiple iterations and lacks a synchronised flow of information between the distributed VR and the BIM environment. Furthermore, existing studies lack rigour in the development and testing of the DVR applications, which will limit their deployment in practice. Also, existing studies were not focused on developing a high-fidelity DVR environment, which is critical for a sector such as the FFE. In various studies [57,70], it has been noted that the visual fidelity of the immersive virtual environment has a positive impact on the user's experience and can trigger more realistic responses. Thus, visual fidelity has a significant impact on the FFE stakeholder's design decision, as aesthetic merit is most valued during an FFE design appraisal [85]. The limited number of literature and the aforementioned gaps could be attributed to the development process for DVR applications being complex and to the infrastructure requirements for such developments that are resource demanding [54]. In a bid to address these gaps, in the present study, a streamlined approach is proposed through the development and testing of a novel collaborative DVR tool for the FFE sector, named COFFEE.

4. Methodology

A novel methodology was proposed for the development and application of a distributed virtual collaborative environment for the communication of FFE design using VR. An exploratory sequential mixed method was subsequently used to validate the developed tool involving 26 FFE stakeholders (Designers, Manufacturers, Contractors, Architects and End-user/Clients). The approach began with a quantitative phase during which questionnaire surveys aided in the elicitation of data related to usability and experience of using COFFEE, followed by a qualitative phase where open-ended interviews were used to obtain FFE experts' perspectives about COFFEE. Fig. 1 illustrates the research framework for this study. The System Usability Scale (SUS) questionnaire [9] was used during the quantitative phase of this study to assess the perceived usability and validity of COFFEE.

The participants' perceived sense of presence (SoP) whilst using COFFEE was measured, as extant research (e.g., [7,12,33,41]) suggested that the sense of presence in the virtual environment has a stronger connection with the usability of the system and will encourage the acceptance of VR technology. Hence, measuring participants' sense of presence (SoP) while using COFFEE was relevant. The Independent Television Commission Sense of Presence Inventory (ITC-SOPI) developed by Lessiter et al. [35] was used to measure participants' SoP whilst using COFFEE focusing on the four key constructs a) *sense of physical space*, b) *engagement*, c) *ecological validity* and d) *negative effect* whilst using COFFEE (refer to Section 6 for further details).

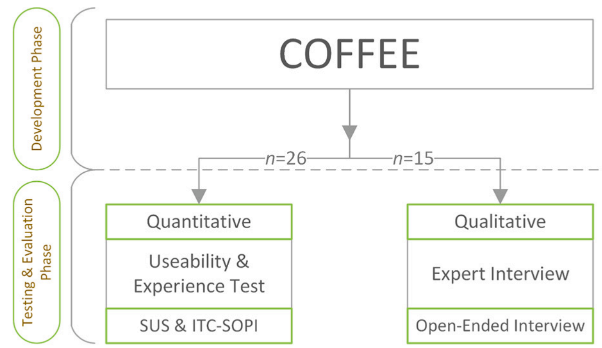


Fig. 1. Research Framework.

The SUS was specifically chosen for this study as the usability assessment tool for the following reasons: *a)* it is one of the most popular and reliable instruments used by HCI researchers for assessing perceived usability [36,37]; *b)* extant research has shown that SUS has a high degree of reliability (Cronbach's alpha coefficient exceeds 0.8) and validity [53]; *c)* there are several ways of interpreting SUS data owing to the extensive normative studies using this instrument [3]; and *d)* SUS can be used on a small sample size with reliable results when compared with other usability assessment tools [76]. ITC-SOPI [35] was chosen specifically to measure the perceived SoP, as it is the most validated and prominently used questionnaire evident in the literature to measure the SoP of users [7,12,79] and produced reliable results [7].

Qualitative interviews were also conducted with 15 out of 26 FFE experts who agreed to participate in an open-ended interview to obtain further options (Table 1). Since applications such as COFFEE as a virtual collaborative tool for communication of design is unique and new to the FFE literature, this uniqueness and newness supported the selection of a qualitative method, as suggested by Amaratunga et al. [1]. The selection of a qualitative method aided in the thematic analysis of the responses which provided further insight into the stakeholders' perspectives on COFFEE. While open-ended interviews are time-consuming and labour intensive, they provide an opportunity for the participants to express their views about COFFEE using their expression and terms thus providing a more personal and genuine perspective [88]. Convenience sampling [24] combined with a snowballing technique [38] was used to recruit the participants for this study because of the peculiarity of the study and the need for participants with expert knowledge of the FFE design related task. Gogtay and Thatte, [28] suggested that convenience sampling combined with a snowballing technique enables researchers to invite participation from a few but most relevant, subjects. Participants for this study were invited using the researcher's social network (LinkedIn and email) and the participation was voluntary.

5. Development of COFFEE

5.1. Overview of system architecture

Given the great potential of the application of VR in the FFE sector, there is a pressing need to address the technical limitation that restricts the ability to access a collaborative virtual environment in which a group of geographically remote stakeholders can interact, communicate effectively and synchronously to appraise designs collaboratively in real-time. COFFEE harnesses a scalable, low-latency, cross-platform cloud-based server which aids in connecting remote users in the virtual environment, the Unity game engine to facilitate a high fidelity virtual environment that enables human-computer interaction (HCI) and a BIM authoring tool to develop the data-rich FFE design. Fig. 2 shows the system-level details of COFFEE which consists of: 1) BIM module, 2)

Table 1
SUS Score, Participant's background information and ITC-SOPI score.

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

*Standard Deviation, ** Participants who took part in the interview.

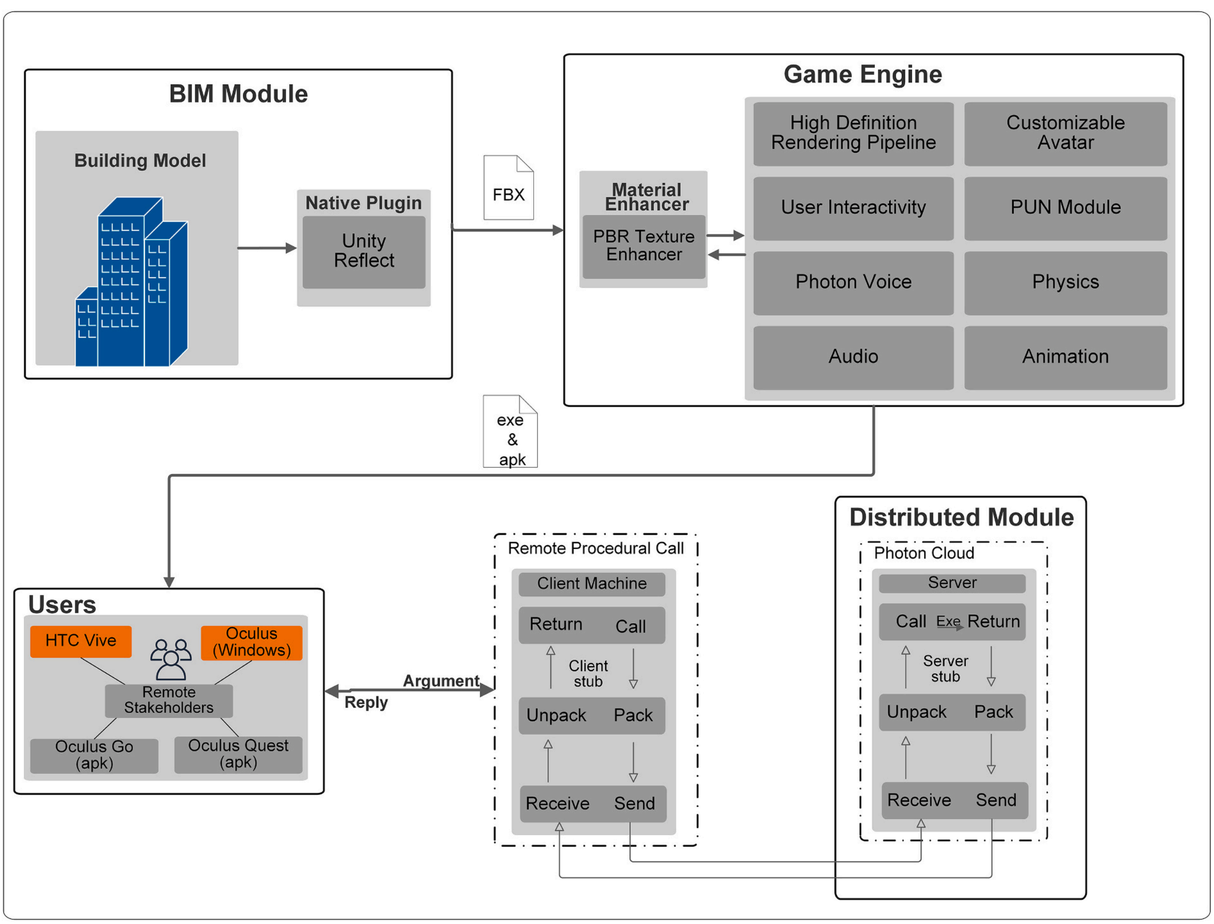


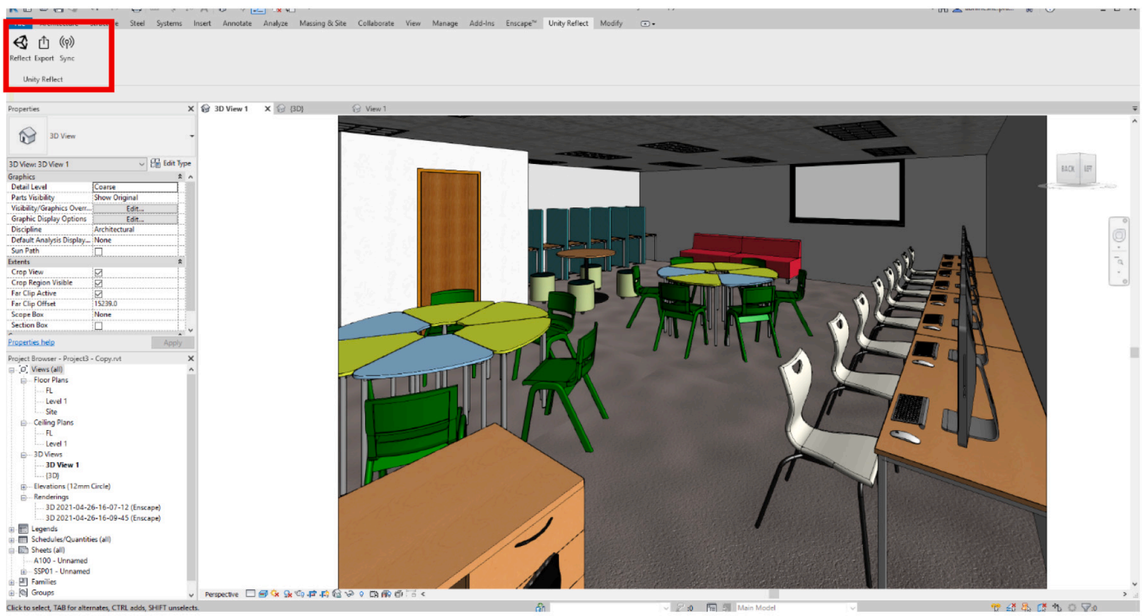
Fig. 2-. System Architecture.

game engine module 3) distributed module and 4) users. Modules (1) to (3) ensures a seamless flow of design information to the users (4). The BIM model developed using the BIM authoring tool was exported into the game engine using Unity3D's native plugin called Unity Reflect [78] in an FBX file format. The model was retextured using a material enhancer application to yield a high visual fidelity.

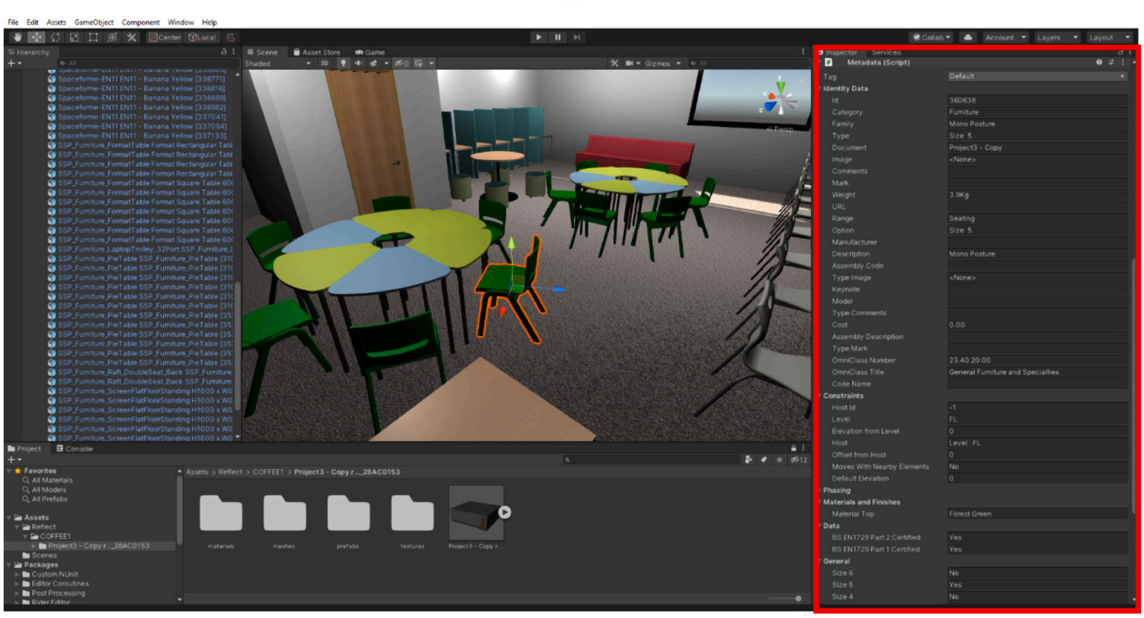
Furthermore, interaction, locomotion, avatar customisation and synchronisation over the network using remote procedure call (RPC), animation and multi-user communication over the network were enabled within the game engine. The developed virtual environment was compiled into an executable file (*.exe*) and an android application package (*.apk*) for multi-platform deployment. User login functionality was provided so that users could enter the collaborative environment with their name tags on the avatar (Fig. 6) which would help co-users to identify each other whilst using COFFEE. After login in with usernames, each user will be directed to a lobby where they have the opportunity to choose their avatar (refer to section *5.3.4* for avatar customisation details). Once the user is happy with the avatar, they can choose the design space they want to review using the interactive option provided in the lobby. The following section provides further details about COFFEE components.

5.2. BIM

The 3D model for COFFEE was developed using the BIM authoring tool Autodesk Revit (Autodesk [56]) which acted as the data source for the proposed system. For this study, two FFE environments *1)* classroom and *b)* science lab for a school were developed for design review using COFFEE. All the required metadata for the FFE design review were attached to the FFE elements modelled in the authoring tools by creating



(a)



(b)

Fig. 3. (a) Unity Reflect Native Plugin within Autodesk Revit, (b) FFE Model in Unity Game Engine with Meta-Data Attached.

required parameters and linking them to the FFE elements. While the stakeholders interacted with the FFE elements, this information was presented in the VR environment on a user interface (refer to Section 5.3.2 for details of the user interface). This made it possible for concurrent stakeholders to manipulate the FFE elements based on various parameters such as dimensions, materials, cost, warranty etc. Furthermore, Unity3D's native plugin "Reflect" [78] was used (Fig. 3) as the interoperability enabler which served two critical functions in the development of COFFEE; *a)* Meta-data translation from the BIM authoring tool to the game engine; *b)* BIM model optimisation before being imported to the game engine. One of the major roadblocks that existed until recently was the interoperability issues between the BIM authoring tools and game engine, such as Unity3D [21]. Even though BIM authoring tools like Revit can generate FBX files that can be imported directly to a game engine, the metadata translations were resource-demanding and not straightforward. It has been observed in some studies [21,34] that there is no streamlined process for importing or exporting geometry between CAD software and game-engine. Further, previous studies (e.g., [84]) highly emphasise the need for middleware applications such as Autodesk3D's max for the metadata translation. Even though this workflow has eased the flow of the BIM model into the game engine without data loss, the iterations required in this process are comparatively cumbersome.

Further BIM model optimisation process aided in reducing the number of polygons present in the BIM model, thereby eliminating the computational load of the graphic rendering, possible frame rate drops and network delays. Eliminating possible frame rate drops and network delays is critical for any networked VR environment such as COFFEE because these performance drops can have a negative impact on the synchronisation of the stakeholder interaction in VR, resulting in a poor user experience that can affect the user's acceptance of VR technology [10].

5.3. Game engine

Unity3D was used as the virtual environment development platform that facilitates HCI in COFFEE. Along with the game engine module, this layer consists of a material enhancer component called Quixel Mixer [56] that aided in the development of a high-fidelity virtual environment. Fig. 4 illustrates the game engine components. The below sections provide further details about the core components of the game engine.

5.3.1. High fidelity virtual environment using material enhancer and HDRP

Fidelity is a general and useful concept for characterising different VR frameworks, which Meyer et al. [46] referred to as "*a measure of the degree to which a simulation system represents a real-world system*". Cooper et al. [18] suggested that the effectiveness of the virtual environment is often measured through the assessment of fidelity. In various studies [57,70], it has been noted that the visual fidelity of the immersive virtual environment has a positive impact on the user's performance and can trigger realistic responses in the user. Thus, visual fidelity has a significant impact on the FFE stakeholder's design decision, as aesthetic merit is most valued during an FFE design appraisal [85]. However, achieving such a higher level of visual fidelity in the virtual environment is a resource-demanding task, as it is necessary to re-texture the materials of the model imported from the BIM authoring tool. Ragan et al. [57] noted that photo-realistic texturing is an effective way of providing a high-fidelity virtual environment. To streamline the workflow of photo-realistic texturing, Unity3D's high-definition render pipeline (HDRP) offers a scriptable render pipeline along with a material

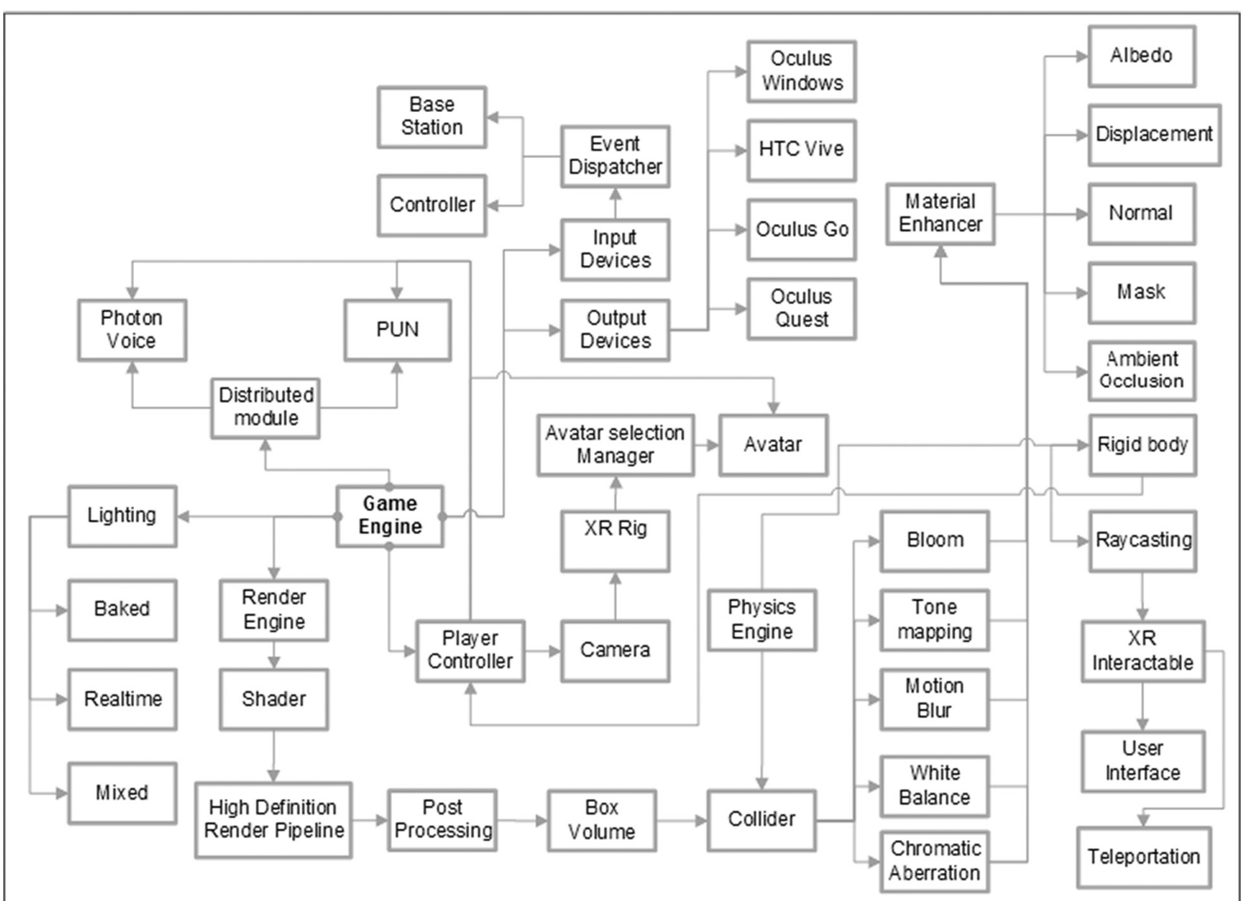


Fig. 4. Game Engine Components.

enhancer application, called Quixel Mixer [56] was used. Fig. 5 illustrates an example of a material conversion process using the texture mapping of the Revit model imported to Unity3D. This material conversion process using the texture mapping of the Revit model imported to Unity3D was applied to all the FFE elements to achieve a high visual fidelity as shown in Fig. 5. One of the challenges faced during the process of texture mapping was the incompatibility between Unity3D's HDRP and the VR integration package, which failed to identify the material of the VR controllers. To overcome this challenge of the incompatibility between Unity 3D's HDRP and the VR integration package, which failed to identify the material of the VR controller, a custom shader graph was developed using Unity3D's shader builder, which was then applied as the controller's default shader graph.

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

5.3.2. *Interface and interaction in virtual environment*

Winestock, [82] noted that developing a user interface that can immerse the users at the same time which will not have any negative effect on the task at hand and the experience of the users is one of the challenges VR developers always face. To overcome this challenge, a hybrid user interface that replicates a digital display with an interactive interface, namely, a virtual handheld tablet display is used (Fig. 6) which is novel in the FFE literature. For the current study, a similar user interface was developed because of its novelty and ease of use. The interface provided an opportunity for the users to manipulate the FFE attributes such as material, texture, cost, and dimensions using the raycast functionality provided on the right-hand controller. These changes were synchronised over the cloud-based server so that co-users were able to visualise the design choices simultaneously. For the current study, Unity3D's XR interaction toolkit was used because of its cross-platform VR controller input. Since COFFEE was developed for multi-platform deployment, the XR interaction toolkit aided in streamlining the development without focusing much on the type of head-mounted display (HMD) used.

5.3.3. *Movement in the virtual environment*

Two types of locomotion methods *a)* natural locomotion and *b)* virtual locomotion were provided in COFFEE for the users to choose based on their comfort. The most common way of virtual locomotion used is teleportation because of its ease of navigation and most importantly it is safer for the users [4]. Also, teleportation is the most acceptable navigation method chosen by the users; as natural locomotion, tends to evoke insecurity and motion sickness in the users [4]. However, COFFEE included both methods of navigation in the environment to understand whether FFE stakeholders make different choices while in a collaborative virtual environment.

5.3.4. *User representation in the virtual environment*

User representation or self-avatar in the virtual environment is thought to have a significant impact on the user's experience in the virtual environment and to affect users' interaction in a collaborative virtual environment such as COFFEE [52]. Further, the finding of Dodds et al. [20] suggested that user representation in a multi-user virtual environment can enhance users' communication. Thus, in the current study, an avatar that was controlled dynamically by head and hand controllers, which were synchronised across the network, was used so that the transforms of each user in the environment were visible to other users. Also, users had the opportunity to choose the avatar's appearance based on their preference using the avatar customisation option provided on the virtual interactive display (Fig. 7). A simple avatar representation with head and hand movements was used in COFFEE because, in studies such as those carried out by Lugrin et al. [42], it was observed that the realism of the avatar in the virtual environment has no effect on the user's task and it was suggested further that simplistic avatar representation is best for faster and more economical development owing to the lower demand on computational resources. It is worth noting that since COFFEE was developed for a multi-platform deployment (HTC, Oculus Quest etc.), computational resources demanding elements that had no effect on the task were deliberately avoided. The avatar asset of Ufuk, [77] was used for the current study because of its simplicity and ease of integration.

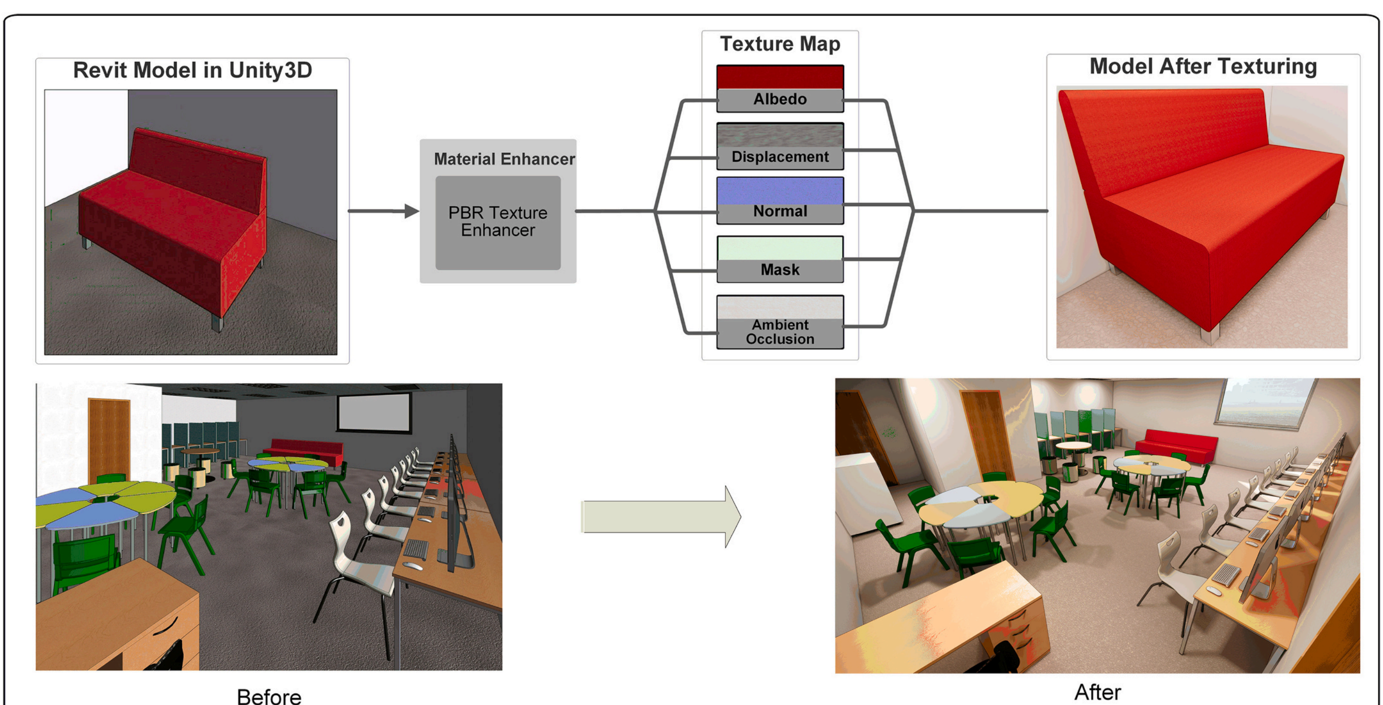


Fig. 5. *Re*-Texturing Revit Model in Unity Using PBR Materials (Classroom Model).

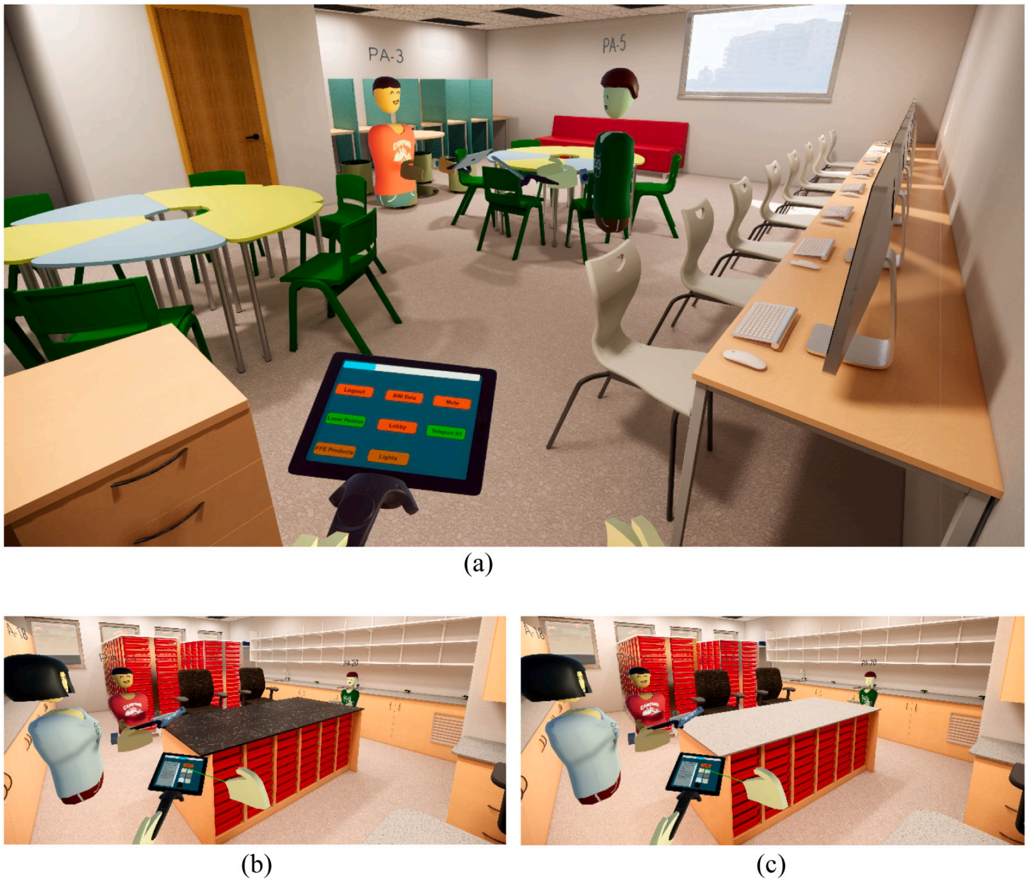


Fig. 6. (a) Stakeholders (avatar representation) engaged in Classroom Design Communication, (b and c) Stakeholders (avatar representation) collaboratively deciding the science lab countertop finish.

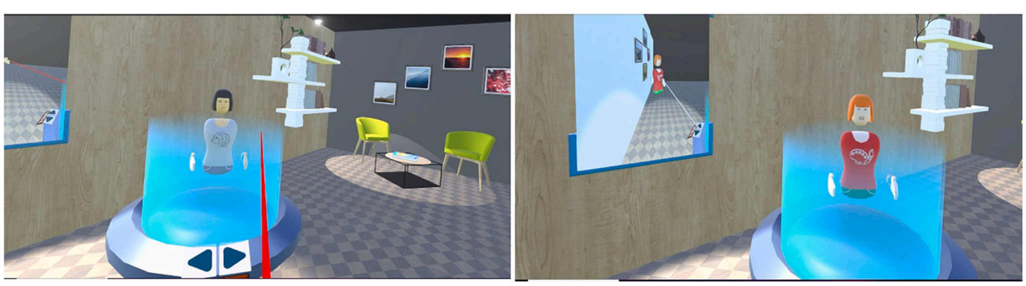


Fig. 7. Avatar Customisation.

5.4. Distributed module

The distributed module is the multi-user enabler in the COFFEE system where it synchronises the users' transforms and the actions relating to design coordination and aids in transmitting voice communication between the users over the network through a scalable, low-latency network. COFFEE utilises the Photon network engine which is a widely used multiuser cloud server [21]. Once the users establish the connection over the network, their transforms and all actions in the virtual environment were synchronised by calling the remote procedure call (RPC) (Fig. 2). Furthermore, users were able to communicate whilst in COFFEE through a voice chat functionality that was implemented over the cloud network using photon voice.

5.5. Users

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

5.6. Integrating COFFEE and scrum for lean construction

Similar to other sectors of the AEC industry, one of the main challenges that FFE stakeholders face while designing a space is to account for the unforeseeable issues, risks and stakeholder requirements iteratively (Oh et al., 2008) [89]. As indicated by Streule et al., [72] as an example, templates, checklists and simulations are used to reduce these unforeseeable risks in a sequential manner. However, the sequential approach requires a considerable amount of resources even before the actual construction starts. Streule et al., [72] observed that it is often necessary to revise plans and drawings significantly by the time construction projects start as a result of modification to project requirements, which can result in cost overruns, schedule delays and low product quality. For a sector such as FFE that operates on narrow profit margins and tight project schedules, the consequences of these unforeseeable issues can have a huge impact on the quality and the sustainability of the sector. In this context, agile project management (APM) methods such as Scrum have proven to be an effective approach to mitigating the uncertainty in a construction project through promoting pragmatism in the organisation, increasing the flexibility of the process and valuing the collaborative work of the human team [11,51]. Among several APM methods, Scrum is based primarily on the process of evolutionary planning and iterations and is one of the most accepted development models because of the opportunity it provides for incremental development of the design that makes it possible to assimilate the changes and fine-tune diversions regarding the expected objectives leading to the continuous development of the project [62]. Importantly Scrum seeks to continue project evaluation and adaptation through rapid stakeholder feedback (Zender & Soto [56]). Further, Scrum works well when the number of stakeholders involved is small, project delivery time is short and high stakeholder interaction and satisfaction are key.

These factors encouraged the integration of COFFEE with the Scrum model for this study. Fig. 8 illustrates a framework for integrating the Scrum model with COFFEE. The Scrum roles presented in Fig. 8 consist of the *FFE Client/representative*, the *FFE design team* and the *Scrum master*. This team is self-organised and cross-functional and all the design decisions are taken within this team who has all the competencies required for the project. The *FFE Client/representative* is responsible for maximizing the value of the project and is also in charge of creating, updating, and prioritising the *product backlog*. A *product backlog* is a prioritised list of various items (e.g., Floor plan, FFE models, FFE specifications, rendered views etc.) which are created during the *Kick-off* meeting. The *sprint backlog* contains items from the *product backlog* which are selected by the *FFE client/representative* and the design team.

The items on the *sprint backlog* are those that the design team believes can reach a *state of done* during each sprint. During the *sprint planning* stage, the FFE design team considers the amount of work required for each item in the *product backlog* and prioritises them to form the *sprint backlog*. Once the *sprint planning* has been completed, the design team starts the development of the design using the *BIM authoring tool*. The developed model is then imported into the game engine to enable interactivity and multiuser functionality which constitutes the COFFEE system. Once the planned designs are ready, they are presented in the *daily Scrum* meetings. One of the benefits of integrating COFFEE with Scrum is that it enables remote collaboration among stakeholders during daily Scrum meetings. The iterations continue until the stakeholders are satisfied with the design. With the utilisation of COFFEE in Scrum workflow, the entire team is able to iterate the design instantaneously

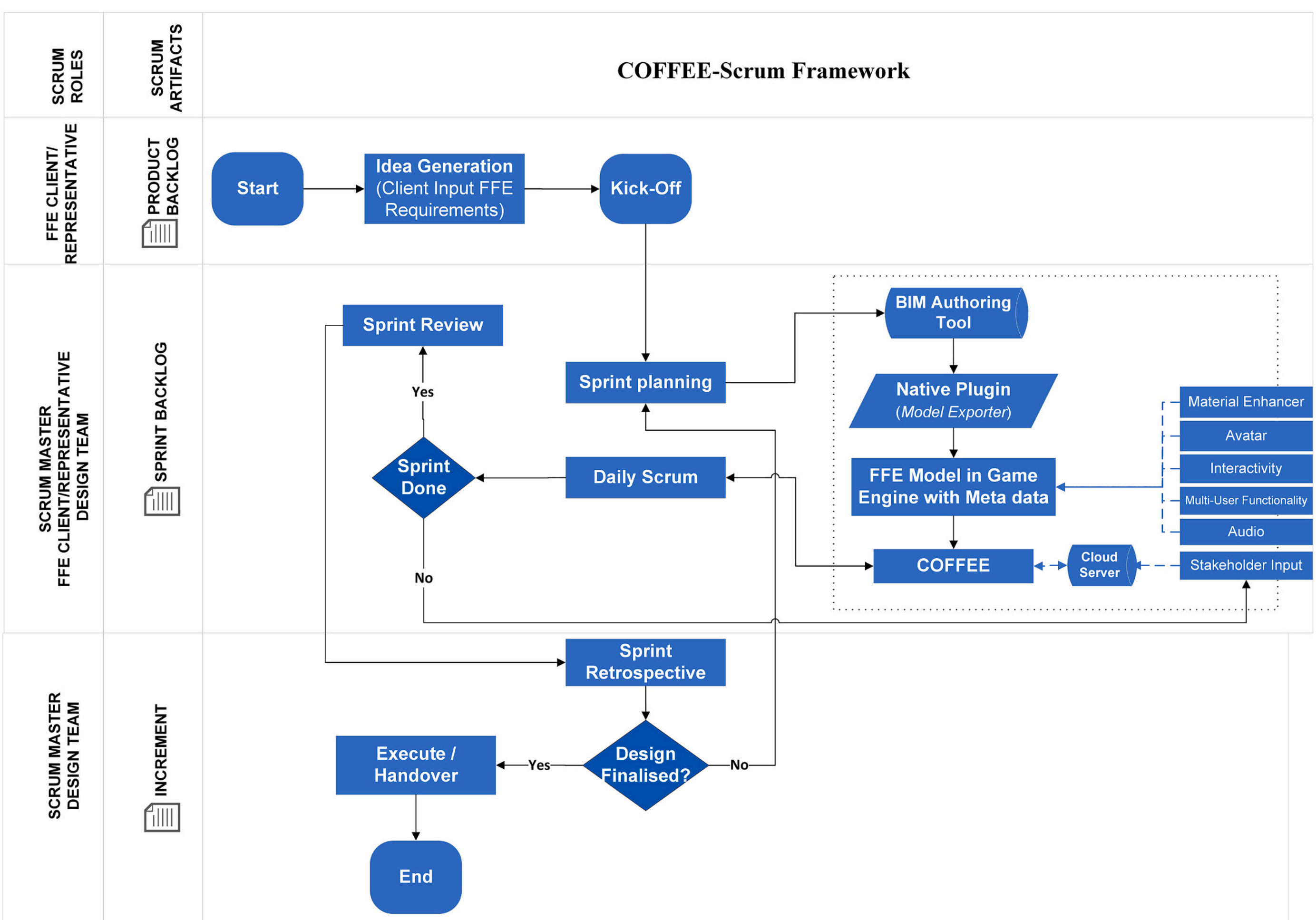


Fig. 8. COFFEE and Scrum Framework.

rather than replanning the sprint. Being able to iterate the design instantaneously further reduces the time taken to achieve the milestones. Once the review of the planned designs has been accomplished, the progress made is reviewed in the *sprint review* stage, followed by the *sprint retrospective* meeting, which is held with all stakeholders to critically evaluate the process and the iterations made to the design. If the *FFE client/representative* is unsatisfied with the final design, then the sprint planning is repeated, and the process continues. Apart from the immersive, interactive and collaborative environment, the screen-short functionality offered by COFFEE to capture the design changes is highly beneficial for Scrum workflow. During the *sprint retrospective*, the stakeholders can utilise these design changes to critically evaluate the process and iterations.

6. Findings and discussion

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

6.1. Testing and evaluation

A series of usability trials were carried out using the SUS [9] to test and validate COFFEE. Also, users' sense of presence whilst using COFFEE was assessed using the ITC-SOPI [35] focusing on the four sense of presence constructs. The trials for the current study involved 26 FFE stakeholders from a diverse age group. Detailed background information about the participants is provided in Table 1. Since COFFEE is a multi-user platform, the participants were invited for testing in groups of a minimum of two participants depending on their availability. However, the maximum number of participants in each group was kept to four based on the availability of the number of HMDs for trial. Before the trial, participants were asked to complete Section (A) of the questionnaire which elicited participants' background information such as profession, age, gender, experience and previous experience using virtual reality. Participants were then briefed on the functionality of COFFEE and a short familiarisation with the user interface and other interactive functionality were provided. Each group was then given 15 min to test COFFEE for various tasks.

It was suggested in previous usability studies [6,58] that 15 min is a reasonable time for assessing the usability of technology. The group had the freedom to choose either of the design space options (Classroom or Science Laboratory). Even though there was no specific task to be completed, the members of each group were instructed to communicate their design ideas within the group and to finalise a design based on their discussion. Following the trial, participants were asked to complete Sections (B) and (C) of the questionnaire which consisted of ten SUS [9] and seventeen ITC-SOPI [35] questionnaires evaluated on a Likert scale with 1 = strongly disagree and 5 = strongly agree. The SUS score ranges from 0 to 100 with a 2.5 increment in steps, where the higher the score the better the perceived usability of COFFEE [66]. The participants were also made aware that half of the SUS questionnaires would sound negative while the remaining half would sound positive and therefore, they should take care while completing the questionnaire. This awareness was important to ensure that the participants interpreted the questionnaire correctly, as the findings of Sauro and Lewis, [65] indicated that approximately 13% of participants responded incorrectly to the SUS questionnaire because of the positive and negative tone. In addition, colour coding (green = positive and red = negative) was used to assist participants to identify the questions with negative and positive tones easily.

The perceived presence in COFFEE was assessed using the shortened version of ITC-SOPI with only the three highest loading items per scale, to have a more economical assessment of presence as suggested by [12], with 17 items instead of 44 items in the full version of the questionnaire. The four factors measured using ITC-SOPI were:

- *Sense of Physical Space* (SPS): is defined as “a sense of physical placement in the mediated environment, and interaction with and control over parts of the mediated environment” [35].
- *Engagement* (E): is defined as the “user's involvement and interest in the content of the displayed environment, and their general enjoyment of the media experience” [35].
- *Ecological Validity* (EV): indicates “the believability and realism of the content as well as the naturalness of the environment” [35].
- *Negative Effects* (NE): are “the adverse physiological reactions such as motion sickness, dizziness etc.” [45].

Participants were then invited to participate in an open-ended interview to elicit further opinions about COFFEE. Owing to the time constraints, 15 of the FFE stakeholders (Table- 1) volunteered for the interview. In the next section, details of the findings from the usability and SoP test and the themes identified from the interview have been presented.

6.2. Reliability of assessment tool

The reliability of the assessment scale was calculated using Cronbach's alpha (CA). Reliability is the extent to which the instrument will yield the same result when the measurements are taken again under the same conditions. Brade et al. [7] suggested that a CA higher than 0.70 for a questionnaire can be considered to be reliable. For the current study, the Cronbach's alpha for the SUS was 0.80 and ITC-SOPI was 0.75, which suggested that both questionnaires were reliable and had sufficient internal consistency.

6.3. Usability evaluation

The SUS score for COFFEE is presented in Table 1. The computing of the SUS score was based on the recommendation by Brooke [9]. The mean SUS score obtained for the current study was 79, which was above the recommended threshold of 70, suggested by Bangor et al. [3] and Brooke, [9] for considering technology to be acceptable. Based on the adjective rating proposed by Bangor et al. [3], the usability score for COFFEE fell between “good” and “excellent” (Fig. 9) thus indicating that the stakeholders considered COFFEE to be easy to use, easy to learn and robust. In general terms, it was interesting to note that the four lowest scores (PA1, PA2, PA23, PA24) were from the participants who are above 50 years of age and some of the highest scores were from participants below 40 years, suggesting that the comparatively younger users were probably closer to technologies such as virtual reality, which was in line with the findings of Bottani et al. [6]. The low usability scores for participants (PA1, PA23, PA24) could also be attributed to their low level of sense of presence scores (Table 1) whilst in the virtual environment, which was in line with the findings of studies (e.g., [7,12,33,41]) that suggested that the sense of presence in the virtual environment has a stronger connection with the usability of the system and will encourage the acceptance of VR technology. Furthermore, it is also worth noting that some of the highest scores were from the architects followed by FFE designers and contractors.

The usability score for COFFEE indicated the acceptance by potential frequent users who found COFFEE to be useful and easy to use. Also, no significant differences in scores when compared with gender was identified ($p > 0.05$). It has been noted in some studies [39] that gender differences affect the perceived usability of technology. However, Bangor et al. [2] identified no differences in the rating of the usability of products based on gender, which was in line with the findings of the current study.

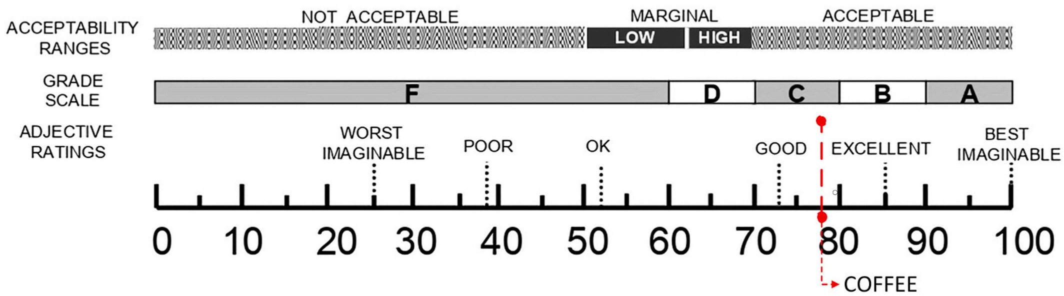


Fig. 9. Grade Ranking of SUS score for COFFEE (adopted from [3]).

6.4. Sense of presence

Table 1 provides details of the ITC-SOPI [35] scores for each of the SoP constructs, suggesting that COFFEE had no or very low, negative effect (NE) (1.30) as well as a high sense of physical space (SPS), engagement (E) and ecological validity (EV). The results from Table 1 suggested that the participants' SPS in COFFEE scored the highest score (4.12) which meant that participants had a higher feeling of "being there" while interacting with the FFE elements and the stakeholders. Further, the EV score was the second highest (4.05) which suggested that the users felt that the virtual FFE environment delivered by COFFEE was sufficiently enough to replicate a response similar to the real-world environment. Furthermore, users showed good engagement (4.00) within COFFEE, which suggested good involvement and interest in the content delivered by COFFEE.

Further, Spearman's correlation analysis [25] was used to identify connections between SoP constructs and usability. To interpret the size effect (r) for significant effects and correlations Cohen's conventions [17] were used. A value of ±0.10 represents a small effect, a value over ±0.30 a medium effect and a value over ±0.50 a large effect. An inverse correlation was identified for the usability and NE ($r = -0.507$, $p = 0.008$), which indicated that the usability of COFFEE can be affected by the negative effects caused by the VR environment, such as motion sickness, dizziness etc. This concurs with the findings of a previous study [48], which indicated that it is necessary to take utmost care during the process of VR environment development to reduce the negative effects of VE. However, the other three SoP constructs showed a low or insignificant correlation to usability. This contradicted the findings of Busch et al. [12], using the CAVE environment, but supported the findings of Brade et al. [7] using a real-world environment. It is worth noting that HMD based VR systems are capable of providing a more realistic and engaging experience than a CAVE system [22,44], that sometimes is sufficiently closer to a real-world environment, which suggests that, apart from the negative effects, no other SoP factors could potentially affect the usability of a system similar to COFFEE that provides a comparatively similar realistic and engaging experience to that of the real world.

6.5. Thematic analysis of expert interview

The interview data collected were analysed using thematic analysis which is often referred to as the most efficient method in analysing qualitative data to capture valuable information [8]. In the current study, a six-phase analysis of the interview data was followed (familiarisation with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report). The main topics of the interview were to discover the usability of COFFEE for improving the FFE's workflow in the communication of design. The participants were informed fully about the research objective, consent procedure and confidentiality issues. The core questions used for the interviews were:

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

In the sections below, each of the themes identified (Fig. 10) has been detailed.

6.5.1. Usefulness

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

"Majority of our projects involve non-technical stakeholders who are unable to grasp the full design. We strongly believe that if we can utilise COFFEE in our workflow, we will be able to deliver an immersive design experience to our clients, at the same time utilise the multi-user functionality of COFFEE to take them through each element in the design as we do in a real-life walkthrough and finalise the design. This will reduce client disappointments, cost overruns due to design changes and importantly we can earn client trust".

This opinion of one of the FFE experts reiterates the finding of Schön, [68], who noted that end-user/client and designers occupy an entirely different design world making design communication challenging. Based on the opinion of the FFE experts, COFFEE could be a game-changer in enhancing collaborative design communication with its stakeholders, regardless of their comprehension capabilities. This reiterates the findings of Chalhoub & Ayer [15] and Du et al. [21] who opined that the opportunity for early involvement of stakeholders (technical and nontechnical) is one of the most important factors that encourage the adoption of distributed VR applications.

6.5.2. Functionality

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

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

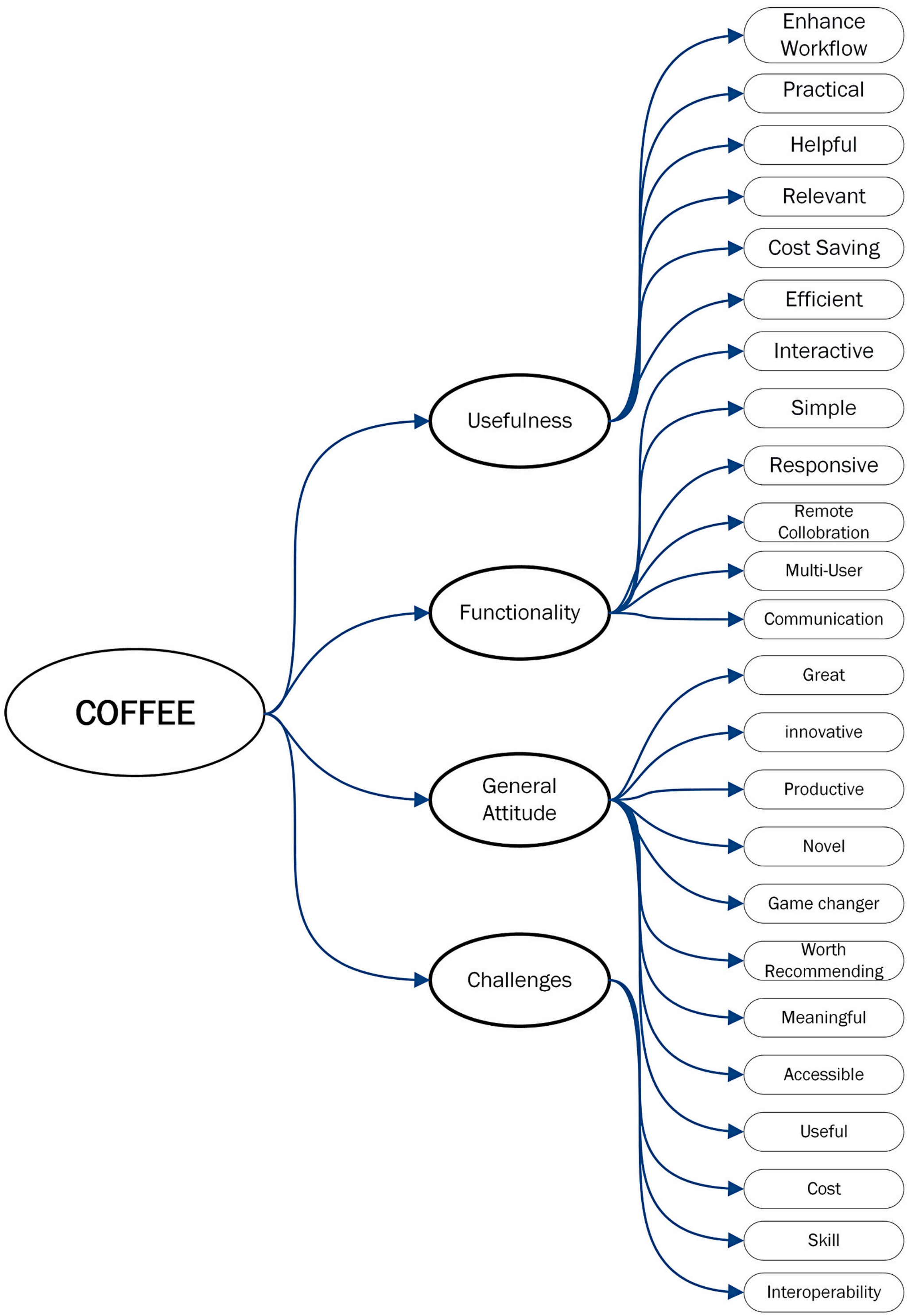


Fig. 10. Themes Identified from the Expert Interview.

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

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

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

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

It is worth noting that studies in which the influence of avatar realism on users' experience in the virtual environment was investigated [29], it was found that, motion-controlled avatars with less realism (similar to the one used for the current study) produced an increased feeling of co-presence as well as positive communication and interaction in the virtual environment. Also, since COFFEE was developed for a multi-platform (HTC, Oculus Quest etc.) deployment, elements placing demand on computational resources that had no effect on the task were deliberately avoided. Furthermore, all the participants (n = 15) opted for teleportation as the preferred means of navigation in the virtual environment, which was in line with the findings of Boletsis and Cedergren, [4]. One of the participants (P13) noted that nausea was experienced while using physical locomotion which led to switching to teleportation mode, which confirmed the findings of Buttussi and Chittaro, [13].

6.5.3. General attitudes towards adoption of COFFEE

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

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

Participants (n = 6) also mentioned that they would highly recommend COFFEE for use in their upcoming projects. Participant (P10) mentioned the possibility of demonstrating the potential of COFFEE to their clients so that COFFEE could be included in their projects for early-stage design. In a study by Mahamadu et al. [43], it was noted that VR-based applications are highly efficient in supporting participatory design where views of elderly end-users are sought during the design process. However, one of the challenges of such VR applications is the feeling of isolation whilst in the virtual environment, especially when the users belong to a vulnerable population. In this context, the application proposed in the present study can eliminate these challenges through the sense of co-presence. Also, in general, Kim and Jo [31] observed that co-presence in the virtual environment can highly improve the productivity and satisfaction of the design process and encourage the adoption of the application.

6.5.4. Challenges

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

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

It is worth noting that the challenge posed by the cost of VR has been reported by many studies [21,27]. Although the recent advancements in hardware and software technology have made VR peripherals more accessible, it has been suggested that providing a high-quality VR environment still requires high-end computer systems with advanced processing units to run them, with additional application development costs [21,27]. As with information technology, attrition of value is also rapid; older systems become obsolete with the rapidly emerging newer technology.

Also, the skills required for the development of a VR environment are another challenge that experts (n = 4) believed could affect the development and adoption of systems like COFFEE. As commented by an FFE expert above, the FFE projects operate mostly on narrow profit margins which limits them from recruiting developers solely for VR development. Adding basic programming modules to the construction education programme is a possible opportunity to develop professionals with multiple skills-sets which then would help sectors such as FFE to recruit multi-skilled professionals without incurring a financial burden. Furthermore, some participants (n = 4) identified interoperability as a challenge that could affect the adoption of such technology. Until recently, several iterations were required for the transfer of BIM models into the game engine which has been reported in several studies [15,21]. However, the recent integration of interoperability plugins like Unity Reflects (similar to the one adopted for the current study) is streamlining the data exchange process far easier than earlier. However, this also points towards the earlier cost constrain mentioned by the experts. Acquiring the licence for the development engine and interoperability tools can also add further costs for the FFE sector.

6.6. Comparison of COFFEE with off-the-shelf VR platforms

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

6.7. Implications

This study proposes a streamlined approach through the development and testing of a novel, collaborative, BIM-based distributed VR application for the AEC industry generally and the FFE sector specifically. This study has significant practical implications. The results of this study provide meaningful insights for guiding decisions in the development of distributed VR applications for the FFE sector. The distributed VR application proposed in this study was demonstrated to have a useability rating between good and excellent. This suggests that stakeholders considered the application easy to use and robust, which is critical for applications such as COFFEE. In a study by Wang et al. [81], it was noted that applications with higher usability ratings tend to have a higher adoption rate. For a sector such as FFE which is on the path towards digitalisation (The British Furniture [75]), a higher usability rating can have a positive impact on adoption. The development methodology proposed in this study will be particularly useful for the practitioner who designs BIM-based distributed VR applications for the FFE sector's use. Existing studies that demonstrate the integration of BIM and DVR indicate that the development of BIM-based DVR applications is challenging, cumbersome and time-consuming as they require multiple iterations and lacks a synchronised flow of information. A more streamlined approach is proposed in the present study towards integrating BIM and the distributed virtual environments with a synchronised flow of information. Furthermore, Song et al. [71] observed that the sense of presence is an important mediating variable in the relationship between usability and efficiency. The assessment of sense of presence in

COFFEE showed higher scores, indicating the usability and efficacy of the proposed distributed VR application for the FFE sector's use. A significant number of participants recruited for this study had >25 years of experience working as FFE designers and contractors in the FFE sector. For this reason, the findings of this study can be generalised and applied easily. This study can be applied, not only in many scenarios of the AEC industry but also to other industries such as the retail segment of the FFE sector, to develop distributed virtual FFE showrooms, as the development and testing presented in this study represent high ecological isomorphism. The present study also provides theoretical directions. The study highlights the importance of the sense of presence in influencing the usability of VR applications. Although the role of sense of presence in a distributed virtual environment has been explored to build a robust body of literature on consumer satisfaction, physiology and training, few studies have tested the concept of presence and its relation to usability in the construction context. Furthermore, the concept of agile project management methods, such as Scrum, has been tested in a few construction literature, albeit its integration with distributed VR environment has never been proposed. The framework proposed in this study will guide both academics and practitioners to integrate immersive VR applications with agile project management methods.

7. Conclusions

Like other sectors of AEC, collaborative design communication plays a crucial role in improving the FFE sector's performance and productivity. In recent years, the FFE sector has shown considerable interest in the utilisation of virtual reality for communicating design among its stakeholders because of its capability of delivering a strong feeling of presence and opportunity for immersive visualisation of design options on a true scale. However, existing systems have not been quite advanced in supporting distributed (multi-user) environments where stakeholders can interact communicate and appraise designs collaboratively in immersive real-time, while at different geographical locations. This paper addresses the VR environment shortcoming by allowing concurrent multi-users to interact, communicate and collaborate virtually during design decision making in the FFE sector through a collaborative FFE environment called COFFEE. COFFEE was tested among 26 FFE stakeholders (designers, contractors, manufacturers, architects and end-user/clients) to understand its usability and the experience of users whilst using COFFEE. Results indicate that COFFEE has a high usability index with an adjective rating between good and excellent. Further, users reported a high sense of physical space, engagement and ecological validity as well as very low negative effects whilst using COFFEE. Analysis of the usability and sense of presence factors revealed an inverse correlation between usability and negative effect. Further no or little significance existed between the other three sense of presence factors and usability scores. Thematic analysis of the qualitative interview with FFE experts ($n = 15$) revealed that COFFEE is a highly useful multi-users VR platform, which is a novel, innovative and productive tool for FFE's application. Experts also noted potential challenges (cost, skill and interoperability) associated with the full-scale deployment of COFFEE. In the current study, it was found that, in practice, COFFEE could be a highly useful tool to assist FFE's stakeholders to communicate design collectively at the early stage of the project. However, it must be noted that, for industries to adopt a system like COFFEE, additional cost and skilled personal requirements need to be considered. Since COFFEE was developed to deliver a high visual fidelity experience, the hardware and software requirement to run such an environment are expensive. Also, the development of such a virtual environment requires skilled personnel, which adds to additional costs. The transfer of data for COFFEE from the BIM authoring tool to the VR development engine which has high visual fidelity that requires several middle-ware applications also adds to the cost of development. For future development, the researchers will look into the integration of COFFEE with low-cost HMDs like Gear VR focusing on widening the accessibility of the application to all levels of stakeholders. However, this process might require limiting certain functionalities and visual quality of COFFEE for a smooth multi-user experience.

Declaration of Competing Interest

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

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