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VR AS A DESIGN MANAGEMENT TOOL.

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1 OVERVIEW

1.1   THE AEC INDUSTRY AND XR TECHNOLOGIES

The Architecture, Engineering, and Construction (AEC) industry is a vast and multifaceted sector that encompasses the planning, design, construction, and operation of the built environment. It plays a crucial role in shaping the physical landscape of our society, ranging from residential and commercial buildings to large-scale infrastructure projects such as bridges, roads, and airports. It is the backbone of urban development, providing the necessary infrastructure and spaces for human habitation, economic activities, and cultural expression [1]. A defining characteristic of this industry is its interdisciplinary nature, bringing together various professionals and stakeholders with diverse expertise; Architects, engineers, construction managers, urban planners, contractors, and facility managers collaborate throughout the lifecycle of a project, from the initial design concept to the final operation and maintenance of the built structure. This collaborative approach ensures the integration of multiple points of view and guarantees the constructed environment's functionality, safety, and aesthetic appeal. The AEC industry also plays a crucial role in driving economic growth and development, as it catalyzes job creation, fostering employment opportunities across a wide range of disciplines.

Moreover, the industry's activities significantly multiplier the global economy, generating demand for raw materials, manufacturing, and services. As a result, the AEC industry contributes to GDP growth and stimulates related sectors such as real estate, finance, and manufacturing. Beyond its economic significance, the AEC industry profoundly impacts society. It shapes the quality of life for individuals and communities, providing spaces where people live, work, and interact. Well-designed and sustainable buildings enhance occupants' health, well-being, and productivity, while thoughtfully planned urban areas contribute to social cohesion and a sense of place.

Furthermore, the AEC industry is crucial in addressing pressing global challenges such as climate change and urbanization, striving for more energy-efficient, environmentally friendly, and resilient built environments [2]. The AEC industry can be further categorized into several sub-sectors, each with a specific focus and expertise. The architectural sector involves the design and visualization of buildings, considering aspects such as aesthetics, functionality, and spatial organization. The engineering sector encompasses various disciplines, such as civil, structural, mechanical, and electrical engineering, focusing on the technical aspects of construction and infrastructure. Construction management involves coordinating and supervising construction projects, ensuring efficient resource allocation, cost control, and timely delivery. Urban planning and design address the broader aspects of city development, including land use, transportation, and sustainability. Finally, facility management oversees the operation, maintenance, and optimization of built assets throughout their lifecycle. The AEC industry plays a crucial role in shaping our physical surroundings, ranging from residential buildings to large-scale infrastructure projects. However, it has historically been characterized by its resistance to change and slow adoption of new technologies. The implementation of advanced

technologies, such as Artificial Intelligence (A.I.), Building Information Modeling (BIM), and eXtended Reality (XR) technologies, faces numerous challenges in this industry. One of the primary difficulties in implementing new technologies in the AEC industry is the inherent complexity and fragmentation of the sector. The industry involves multiple stakeholders, including architects, engineers, contractors, and facility managers, who often work in silos, using different software and methodologies [3]. This lack of interoperability and collaboration hinders the smooth integration of new technologies. Moreover, the construction industry has traditionally relied on conventional practices and established workflows, making it resistant to change. The fear of disruption, cost implications, and a lack of understanding about the potential benefits of new technologies further contribute to the hesitancy in their adoption [4].

However, the AEC industry has recently witnessed growth in the implementation of more advanced technologies in its processes. Companies and design offices worldwide are recognizing the potential of technologies like A.I.s, XR, and IoT (Internet of Things) to improve their operations, enhance collaboration, and deliver better project outcomes. These technologies are no longer considered as mere ornaments of forward-thinking; they have practical applications and the potential to transform working practices and discipline processes. Among these new technologies, one of particular interest is Extended Reality (XR) with its subcategories Virtual Reality, Augmented Reality, and Mixed Reality. The panorama of possible applications of these technologies in the field has continually been widening, and the research interest is increasing accordingly. A review conducted by the University of West of England Bristol in collaboration with Cardiff University and Loughborough University in 2020 identified the six application scenarios representing key implementation areas for Virtual Reality and Augmented Reality technologies in the construction industry. The result of this investigation (Figure 1) represents an essential milestone for researchers because it classifies quantitatively the general levels of VR and AR adoption by companies and professionals of the industry on a scale from 0 to 5 (where 0 represents the lowest grade of implementation and five full-force implementation).
As this study demonstrated, eXtended Reality technologies are effectively implemented in each of the six application scenarios identified (namely Stakeholder engagement, Design support, Design review, Construction support, Operations & Management, and Training). More importantly, the result of this research shows that both AR and VR present a level of adoption higher than 1.5 per group, demonstrating their applicability in support of AEC processes [5].

The growing relevance of XR technologies for the Architecture Engineering and Construction industry is underlined by another important research. In 2022, a study conducted by the University of Lisbon set out to corroborate the incremental importance of these technologies throughout the years, analyzing relevant research material aiming at understanding how much XR activity in the AEC industry has been conducted since 2011, classifying which areas have seen the most contributions and which types of XR technologies have been used the most [6]. The results of the research demonstrated a radical growth (and consequent increase of interest) towards these technologies, reaching almost 152 dedicated

studies in 2022, with a steep increase in the period between 2016 and 2019. More importantly, the study provided insights into the evolution of the number of XR primary studies for the three areas of the AEC industry, showing a steady and almost equal increase in the number of research studies per each (Figure 2).
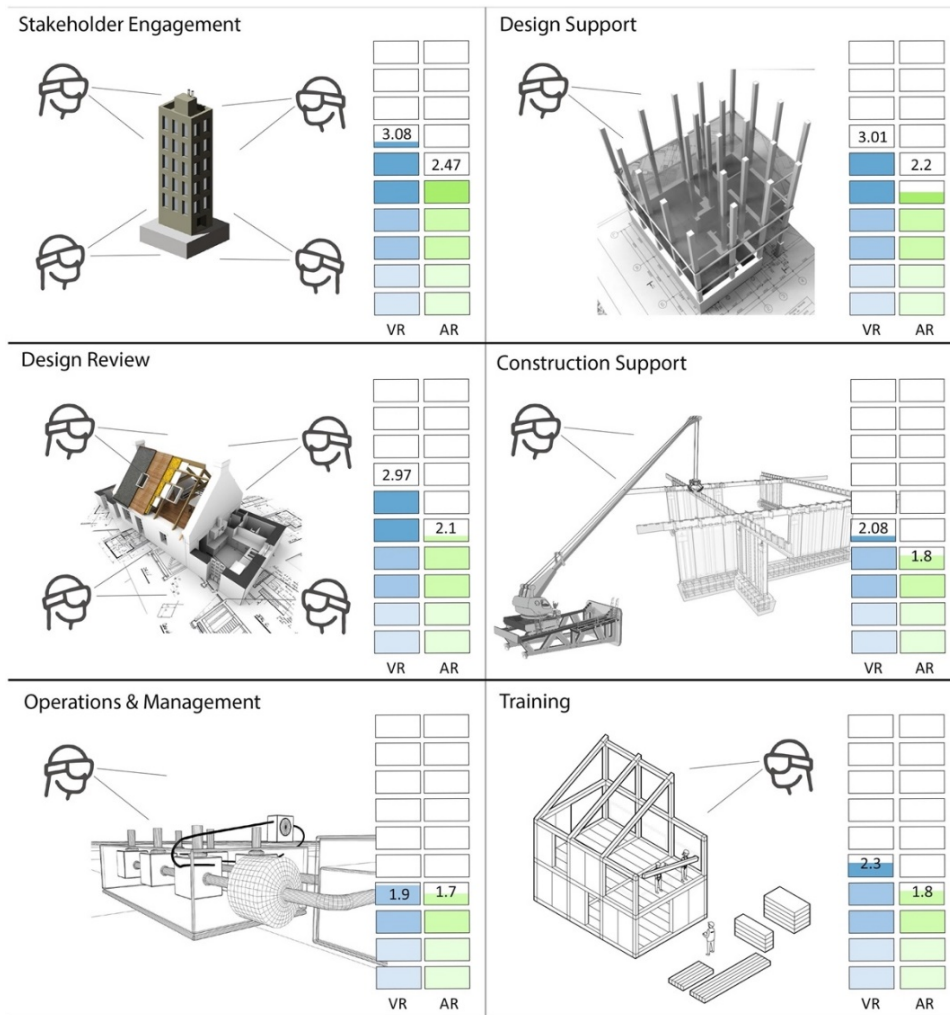
Figure 1 – From [5] *AR and VR cases in the AEC sectors and their estimated levels of adoption.*

Most notably, the study addressed the maturity of the different XR technologies, assessing the collected data in lieu of the type of XR utilized. The result led to demonstrating how Virtual Reality is the most addressed type of reality with 597 dedicated researches that account for around 60.7% of the total collected. AR comes next with 432 studies, which weigh 44.1% of the total, while MR encompasses only 5.3% with 52 studies.
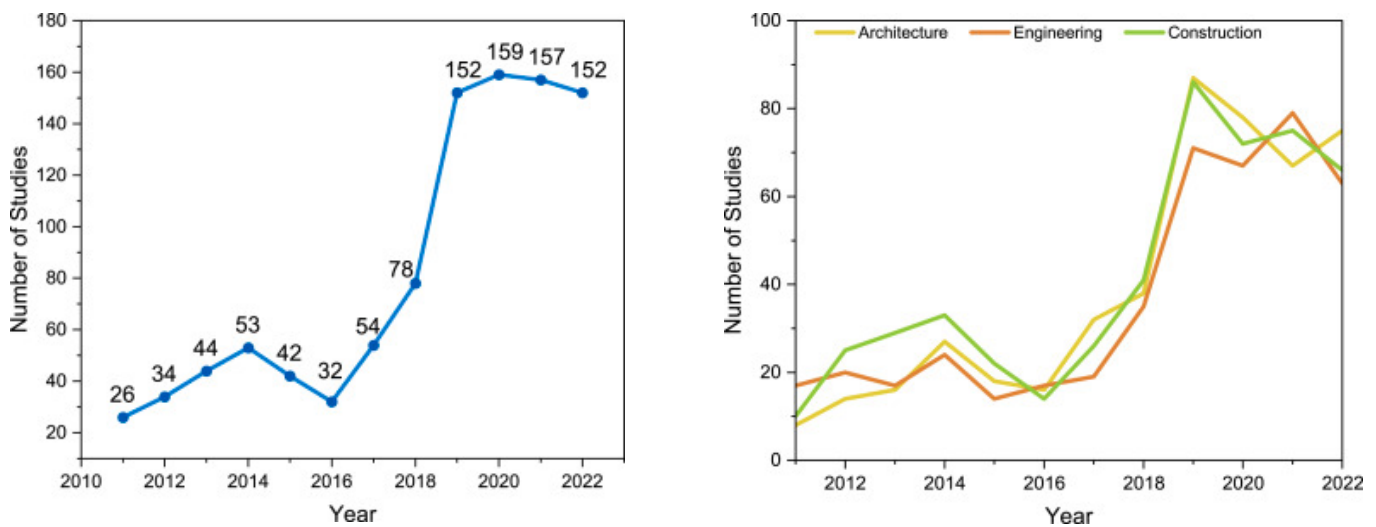
Figure 2 – From [6] *Evolution of the number of relevant primary studies (published 2011–2022 and evolution of the number of XR primary studies for each AEC area.*

In 2020, the University of California conducted a study on another topic that shows how the AEC industry is increasingly embracing XR technologies in its processes. The research aimed to assess the cooperation between academia and the work environment, analyzing the quantity and quality of studies conducted with the aim of developing a tool for the implementation and the benefit of the AEC industry [7]. Specifically, the study aimed to understand if and to what extent the research on XR technologies considers the feedback and direct support of AEC professionals. The study collected and analyzed a total of 201 papers about the implementation of XR technologies in the AEC industry, and it classified the data into three main groups, deepening on the type of contribution provided, namely the creation of a prototype, the use of the technology for a direct experiment, or a purely theoretical approach. For each paper collected in the three groups, the research verified the extent of the professional contribution brought to the outcome of the study and the number of times the same type of contribution has been sleeked out by the researchers. Interestingly, it was highlighted that only 2% of the 201 analyzed cases were subject to architects and other AEC professional confrontation and feedback, unveiling the need for higher consideration of professional inputs to develop tools truly dedicated to real practices.

Although generally more reluctant than other industries in the experimentation of new technologies and slower in their adaptation and implementations, the advent of Industry 4.0 [8]and changes that have come along [9] have boosted the Architecture Engineering and Construction industry into a more aware and technology-ready state. This research is based on such a predicament and sets out to explore and support the development of one of the new technologies that are now becoming an integral part of the AEC processes.

2 OBJECTIVE

2.1   PREMISE

Provided the demonstrated contribution that XR-BIM systems offer to the AEC industry throughout the different phases of a project life cycle [10], one major issue remains, and it concerns the general adaptability to standard AEC processes. Although highly effective when implemented in the workflow, XR-BIM technologies remain tailored to the process they are created for and that aimed to enhance or support.

To fully understand the problem, it could be insightful to use technological parallelism with Artificial Intelligence [11]. It is known that the current status of A.I.s development level can be addressed as "narrow intelligence" [12] against the "general intelligence" that scientists have been trying to reach for almost 60 years. Narrow intelligence A.I. differs from the general one as its functionalities and capabilities are limited (although highly perfectioned) to the sole task that the algorithm is developed to address. On the contrary, "general" A.I.s are meant to be entirely intuitive and adaptable to any given task, allowing an algorithm initially created to guide self-driving cars and also to acquire the skills to play chess and to develop business strategies [13]. Similarly, it is still virtually impossible to develop and implement a "one-size-fits-all" XR-BIM solution that can be comfortably applied to each and every process scenario or any given stage of a project life cycle. The impossibility of creating such a system comes from different factors, such as the technological differences among various types of eXtended Reality technologies, the many typologies of BIM platforms, and, in general, the various information formats and exchange protocols involved [14].

Provided that such a "general" system is unfeasible, it is currently possible to operate a partial generalization of XR-BIM system implementation in the AEC workflow, explicitly aiming at project management. Software houses recognize the importance that eXtended Reality technologies represent for Architecture Engineering and Construction and have begun to develop XR-BIM systems for Common Data Environment (CDE), allowing for more general and wide-span use of these technologies in the AEC industry.

2.2   RESEARCH GOAL

The primary goal of this Ph.D. research is to present and explain the improvement matrix formulated to benefit the ongoing development of the beta version of UsBIM.Reality a Virtual Reality application of the Italian software house ACCA Software that operates solely as an add-on to the proprietary CDE system developed by the same software house. The research does not aim to provide computational or coding

contributions to the software, and no line of code has been generated and implemented in the application directly.

On the contrary, the work conducted sets out to enhance specific features of the VR software, which serves to enhance its performance from the final user's perspective. This research focuses solely on the VR application, and it does not engage in recommendations or improvements for the base CDE that UsBIM.Reality operates on.

This study aims to produce a set of key recommendations that target specific aspects of the VR software and its functionality through implementation tests on a real case scenario represented by a multistory residential building in Dubai. The objective is to support the software house developers in addressing and potentially solving software faults or inadequacies from a usability and operability standpoint. The research work focuses in particular on enhancing the functions associated with project management that the prototype of ACCA Software displays through its collaboration with the CDE base software (called usBIM.Browser), in terms of:

- Program Logic = The functioning and input-output base of the software.
- User Interface = The medium used by the user to input information into the program.
- Graphics = The quality and typology of visual inputs/outputs of the program.
- Modeling = The process of interacting with the BIM model or parts of it.

3 INTRODUCTION

3.1 OVERVIEW OF XRS TECHNOLOGIES

Extended Reality (XR) technologies encompass a spectrum of immersive technologies that blend virtual and real elements to create interactive and multisensory experiences. The concept of XR is rooted in the "reality-virtuality continuum" framework, which was first introduced by Milgram and Kishino in 1994 (Figure 3). This framework defines a range of environments that extend from Physical Reality to Virtual Reality, with augmented Reality positioned in between. At one end of the continuum lies physical Reality, which refers to the real-world environment we perceive through our senses. It encompasses the tangible objects, spaces, and interactions that constitute our everyday experiences. On the opposite end lies virtual Reality (VR), a technology that, while in use, provides the user with the fully immersive sensory experience of a computer-generated reality that creates an artificial setting that can exist outside any relationship with the actual world and the user can explore it via specific and dedicated hardware [15]. Augmented Reality (AR) occupies the space between Physical Reality and Virtual Reality. It enhances users' perception of the real world by overlaying digital information or virtual objects onto the physical environment [16]. This augmentation is designed to supplement or enhance our sensory experience of the real world, providing additional context, information, or interactive elements [17].
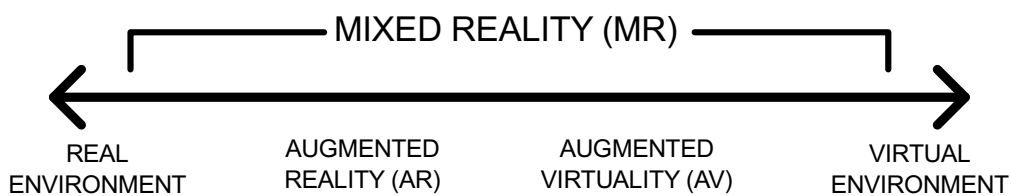
Figure 3 - From hardware [15]:representation of "Virtual continuum".

XR technologies encompass both VR and AR, as well as mixed Reality (MR) and augmented virtuality (A.V.). Mixed Reality refers to environments where virtual objects are seamlessly integrated into the real world, enabling interaction and coexistence between the virtual and physical elements. MR often involves the use of head-mounted displays (HMDs) that overlay digital content onto the user's field of view, allowing for spatially registered interactions and accurate 3D world locking.
Augmented virtuality, on the other hand, refers to environments where real-world elements are integrated into virtual environments. This integration can involve the use of sensors, cameras, or other technologies to capture and incorporate real-world objects, people, or events into virtual simulations or experiences.
The versatility of XR technologies allows for a wide range of applications across various industries, including healthcare, education, gaming, architecture, and more. XR technologies offer unique

opportunities for immersive training, simulation, visualization, and interaction, enabling users to engage with digital content in a more natural and intuitive manner [18].

3.1.1 VIRTUAL REALITY OUTSIDE THE AEC INDUSTRY

Unsurprisingly, the gaming industry is not only the main driver for the development of VR-related technologies but also one of the industries that benefit from its implementation the most, providing users with immersive and interactive gaming experiences that enhance the overall gameplay and entertainment value [19]. The impact that VR is demonstrating in this industry is well documented and has proven to be a "game-changer" technology for a sector continuously striving towards novelties and embitterment [20], to such an extent that developers and software houses are sponsoring research aiming at busting interaction among players while in the VR environment mimicking a social media platform [21].

Virtual Reality is already abundantly used in other sectors, such as healthcare, where it is applied for the treatment of psychosis. Doctors implement immersive virtual scenarios of everyday life, helping patients overcome their fears [22]. Virtual Reality proves valuable in the training of physicians, especially in support of musculoskeletal procedures or helping patients with their physical rehabilitation [23]. Virtual Reality has also proven successful as a medical consultation platform, providing a virtual office for the physician who can access all patient-related information simultaneously, thus facilitating diagnosis [24]. Other works have demonstrated that this technology can be successfully used to simulate surgical procedures, allowing medical professionals to practice and refine their skills in a safe and controlled environment [25] [26].

Education is another area of extensive implementation for Virtual Reality that has proven to be a valuable tool to stimulate and even the learning experience [27]. This technology applies in the education industry as a medium to create virtual laboratories, facilitating the acquisition of practical chemistry skills in a safe and non-hazardous environment while supporting communication and collaboration among students [28]. VR enables students to engage in realistic simulations and hands-on experiences that would otherwise be difficult to replicate in a traditional classroom setting, and it also allows for distance-teaching approaches based on interactive collaboration in virtual spaces [29]. The blend of visualization and interactivity proper of Virtual Reality fosters active learning among students while creating a peaceful study setting that enhances concentration levels and improves content retention [30]. Furthermore, this technology allows for radically new approaches to teaching via so-called "serious games" learning experiences. Rather than passive observers, users engage in those learning environments as active participants, permitting the development of exploration-based learning paradigms [31].

3.1.2   VIRTUAL REALITY IN THE AEC INDUSTRY

The adoption of VR in the AEC industry is gaining momentum due to the exponential advancement in gaming engines and the increasing affordability of dedicated hardware, which are easing the assimilation of this technology into typical workflow [32].

VR is mostly implemented to boost stakeholders' engagement and project buy-in, support decision-making, and generally assist in the design process [5]. VR can, i.e., offer end-users a better understanding of the final livability of the designed space way ahead of the project completion, often leading designers to re-think and improve their projects through an actual participated design [33]. VR simulations allow potential buyers to explore real estate properties virtually, enhancing their understanding of the environment and increasing the likelihood of closing a sale [34]. In particular, studies have been conducted to evaluate relationships between emotions driven by the atmosphere in the virtual environment and the subsequent influence of emotions toward house purchase intention, finding that the virtual visit can indeed stimulate and enhance the buyer's desire to purchase [35]. Additionally, this technology has been revealed to be impactful also in the case of stockholders' engagement, facilitating discussion and decision-making on projects by providing a shared virtual space for collaboration [36]. Professionals of the AEC industry can benefit from the use of VR technology in their design endeavors by gaining a more perceptible understanding of proposed solutions and their impact on the project [37]. Furthermore, numerous studies are now approaching the collaboration of this technology with another fundamental predicament of the AEC industry, such as Building Information Modeling, highlighting the importance of this relationship and the benefits that can be derived from it [38], [39].

3.1.3   AUGMENTED REALITY OUTSIDE THE AEC INDUSTRY

Also Augmented Reality finds successful applications in various industries other than Architecture, Engineering, and Construction. Several works have demonstrated that the perceived value of this technology for hospitality and truism is underestimated in comparison to the actual market benefit that it produces [40]. The relevance of this technology in hospitality is growing to such an extent that researchers are developing new benchmarks and measurement scales to define and validate its effectiveness on consumers' perceptions and buy-in [41]. AR technology proves versatile and impactful as it can provide interactive guided tour experiences with real-time translations, enhancing historical sites' value and helping heritage culture reach a wider audience [42]. Furthermore, it can also be impactful for tourism and hospitality marketing purposes. Case studies have, in fact, demonstrated that Augmented Reality can be used to enhance the customer experience by providing pre-hotel-booking virtual visits or enriching the culinary journey via the addition of an intercave layer to the dining experience [43].

AR has been effectively applied in the healthcare industry as well. Case studies have demonstrated the effectiveness of this technology for the assessment and treatment of psychological disorders, where the use of AR can increase the patient's emotional engagement to the buy-in of the proposed therapy [44]. This technology proves versatile in support of both physicians and patients. Research

demonstrated its effectiveness during cardiac surgical procedures, where it helps specialists by providing real-time guidance and information during complex surgeries [45]. It can also create interactive and immersive experiences for patients, assisting them in managing their conditions and providing therapeutic support [46].

In the education industry, AR is employed to increase students' focus and stimulate the learning process. By overlaying digital content onto physical textbooks or learning materials, AR provides interactive and engaging experiences, making learning more enjoyable and effective [47]. The support that Augmented Reality represents for both educators and students is well documented in the literature, which presents corroborating results on the matter for almost twenty-five years [48]. Different studies have, in fact, proven the positive impact that this technology has on the learning curve of students, especially when implemented as mobile game-like systems [49], while other researchers have been focusing on studying and developing new pedagogical strategies to support the implementation of this technology [50].

The media and advertising industry have also embraced AR technology to guide and direct consumers' behavior[51]. Through interactive AR experiences, companies can deliver personalized and immersive advertisements, enhancing customer engagement and brand awareness [52]. Numerous empirical studies have been conducted to evaluate the effectiveness of this medium in guiding consumer choices and advertising responses [53].In the retail sector, AR is used to benefit sales and create additional value for customers. For example, customers can use AR applications to try on virtual clothing or visualize furniture in their homes before making a purchase [54]. Augmented Reality has been, in fact, proven to outperform web-based product presentations by generating greater immersion and enjoyment for costumers and consumers [55].

3.1.4 AUGMENTED REALITY IN THE AEC INDUSTRY

Augmented Reality provides significant contributions to the AEC industry, particularly in support of the construction stage, enhancing users' perception of the project under development by integrating digital assets on top of the physical world and thus facilitating inspections [56]. AR is, in fact, largely used for daily on-site project walkthroughs, helping workers better understand their tasks in relation to the expected outcome and facilitating the correct performance [57]. Studies have also demonstrated the efficiency of this technology in supporting site work by monitoring construction progress, facilitating site inspections, and easing daily assembly tasks [58]. I.e., research has proven how Augmented Realty, in tandem with BIM technology, can support and speed up routine inspections of fire safety equipment in comparison to traditional paper-based methods [59]. Other studies have focused on the materials and parts fabrication aspects of the building lifecycle, demonstrating the positive impact that Augmented Reality can have on the related processes [60]. Finally, AR also plays a crucial role in building operation and management, assisting professionals in retrieving, delivering, and sharing information related to building maintenance and facilities management [61], [62].

3.1.5   MIXED REALITY OUTSIDE THE AEC INDUSTRY

Mixed Reality (MR) is a technology that combines virtual computer graphics objects with a real three-dimensional scene, creating an interactive overlap between the real and virtual worlds [63]. MR offers immersion, information, and interaction, providing users with a user-centered and natural experience [64]. It has been adopted in various industries, including education, healthcare, entertainment, robotics, e-commerce, and retail [65].

In the education sector, MR is used to support and facilitate remote teaching, enabling educators to deliver immersive and interactive lessons to students while enhancing their interest and engagement to make learning more enjoyable and effective [66]. Mixed Reality can also change the way educators deliver information. This technology can blend tangible and physical contents with virtual ones, changing the way the teachers and students interact in the classroom [67].

In healthcare, MR is utilized for training purposes, allowing doctors and trainees to practice medical procedures on realistic mannequins [68]. It is also used in empathy classes, providing healthcare professionals with a better understanding of patients' experiences, and improving their ability to deliver empathetic care [69].

The entertainment industry has also been exploring the potential of Mixed Reality. This technology can positively impact consumers' experiences by increasing the captivating factor of created content. Specifically, studies targeted the effectiveness of this technology in increasing the "wow" effect of live performances via MR HMD worn during the show [70]. The arts, specifically moviemaking, can also benefit from the use of this technology. Research has been conducted on implementing Mixed Reality as a medium for consuming interactive movie trailers [71] and creating more engaging and socially interactive art shows where viewers can actively participate in the performance [72].

In the field of robotics, MR enables users to interact with objects through MR interfaces, while linked robots execute the same manipulations in the real environment with potential applications in areas such as manufacturing, automation, and teleoperation [73]. This technology is also used to facilitate and ease the robots' programming. Via the use of HoloLens (one of the MR HMDs available in the market), researchers have performed studies on how to train manufacturing robots successfully via the implementation of MR technologies [74].

E-commerce and retail are also investing in MR due to its interactive features and the potential for business growth that this technology represents for these industries [75]. MR enables interactive product visualization, where customers can virtually try on clothing, test virtual makeup, or place virtual furniture in their homes before making a purchase [52]. This type of solution enhances the shopping experience and helps customers make informed decisions. Similarly, studies have demonstrated the effectiveness of this technology in support of customers' retail experiences. Mixed reality can, in fact, impact the product buy-in time, and it helps customers better grasp the utilitarian/functional aspects of the purchase[76].

3.1.6   MIXED REALITY IN THE AEC INDUSTRY

Provided that Mixed Reality is the most "infant" among the XR technologies, it shows promising results in AEC implementation, especially for on-site design review and multi-user collaboration, particularly supporting cultural heritage projects [77]. Studies have also demonstrated the effectiveness of this technology in support of real-time communication and interaction among team members in a collaborative blended environment, where stakeholders could have design coordination sessions wearing MR HMD and simultaneously interact with peers and the project hologram [78]. Numerous research studies have also demonstrated the validity of this technology in supporting design analysis and facilitating decision-making processes for architecture and interior design by visualizing and interacting with virtual models in real-world contexts through a blended experience. I.e., a study was conducted to corroborate the extent of MR contribution to the reduction of design error detection tasks, demonstrating not only a reduction in completion time but also a lower mental stress [79], [80]. Finally, MR technologies contribute to the processes related to the construction and operation stages by providing professionals with improved access to information and enhancing data visualization [81].

3.2   IMPLEMENTATION PLATFORMS: BIM AND CDE

Building Information Modeling (BIM) is a collaborative way for multidisciplinary information storing, sharing, exchanging, and managing throughout the entire building project lifecycle, including the planning, design, construction, operation, maintenance, and demolition phases [82]. BIM is a well-established technology in the AEC industry today, and it has existed (although in more embryonal forms) since the 1970s [83]. The base of Building Information Modeling is an information-rich multi-dimensional virtual model of a facility (existing, under design, or development) that functions and is regarded as a knowledge repository of the project, which can be effectively considered a "digital twin" of the real-life project (Figure 4). The capability of storing, interrogating, cross-referencing, and cross-using project data makes BIM the perfect "connection and exchange" platform for all AEC players. The interoperability of the information generated by a BIM model makes it a hub for all AEC industry specialists. It fundamentally facilitates every aspect of the project life cycle while limiting information loss in the passage from one project life phase to another [84]. Being a "dedicated" technology, BIM finds implementation only in the AEC sector and related fields. However, its potential has not yet been equally taken advantage of in every phase of the building life cycle. It has been pointed out that while the design and construction phases are well attuned to the process of Building Information Modeling, the planning and operation phases fail to implement this technology as effectively [85].
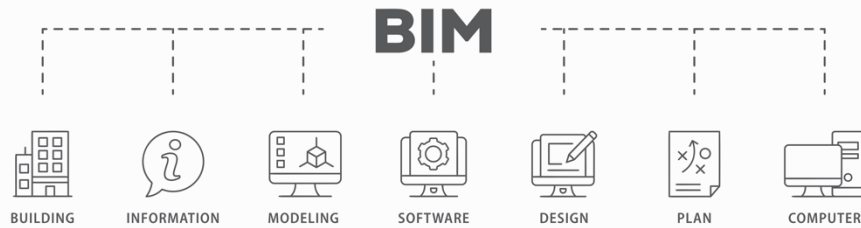
Figure 4 - BIM infographic.

Common Data Environment (CDE), on the other hand, is "a single platform or group of integrated IT solutions which provide a centralized repository for the collection, management, and dissemination of project and asset information through a managed process" [86]. If BIM shall be addressed as the digital twin of the project, the common data environment is the cloud entity that allows its existence. CDE is essentially the domain-specific collaboration platform onto which all stakeholders, via different levels of permission access, can cooperate while exchanging, controlling, sorting, and validating any type of project information using BIM philosophy [87]. One of the first and most famous CDEs can be considered the Aconex Platform, which was developed by Aconex in 2012 and later acquired by Oracle in 2017.

Today, the panorama of cloud systems for the AEC industry that presents Common Data Environment characteristics is quite ample, and, among many others, it is relevant to mention Autodesk BIM360 and Trimble Connect, given their large-scale adoption [88]. There are several benefits related to the implementation of a CDE system for the management of a project. Common Data Environments (Figure 5) are much more than information cloud repositories. This technology allows for full access, visualization, and operations on all the instances related to the project, of which the BIM model is only one of many others [89], but above all, this technology serves the purpose of enhancing, facilitating, and controlling the creation and exchange of information among all the project stakeholders (if the access is authorized and granted) [90].
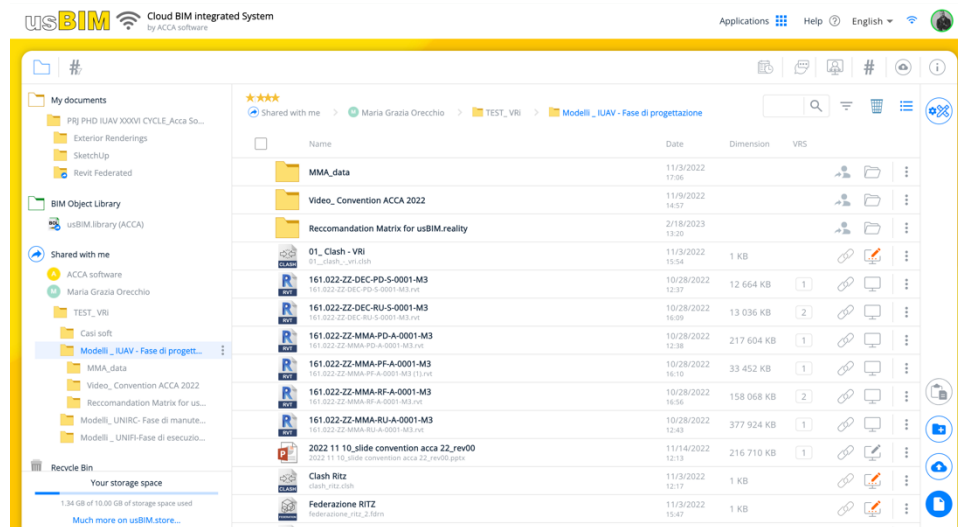
Figure 5 - usBIM.Browser, ACCA Software CDE.

3.3 RESEARCH BACKGROUND

Although there is continuous growth in the body of literature related to XR technologies in the AEC sector, the number of papers presenting actual breakthroughs in the field is quite limited. This scarcity of influential research can be attributed to various factors that hinder the implementation of XR technologies in firms and companies. These factors include the lack of specialized personnel to support companies in their experimentation and the high technology costs associated with XR technologies, which often result in a low return on investment for mid-size offices. Moreover, concerns about the adaptability and usability of XR technologies in the early design processes and workflow of the industry persist, posing challenges to their widespread adoption in the AEC sector, as highlighted by the Universidad de Lisboa in collaboration with The Pennsylvania State University [91].

A comprehensive study conducted in 2020 by the University of West of England Bristol in collaboration with Cardiff University helped gain an in-depth understanding of the factors that limit the adoption of VR and AR in the AEC industry, identifying four main challenge categories. The first one relates to the immaturity of these technologies, such as the weight and limited battery life of head-mounted displays. The second category encompasses the specific requirements for implementing VR and AR, including the absence of standards for data exchange. The third category involves issues related to the structure of the AEC sector and the dynamics between clients and contractors. Finally, non-technical challenges, such as difficulty accessing expert knowledge, also contribute to the limitations of XR technology adoption. Despite these challenges, the significance of XR technologies for the AEC industry is expected to experience exponential growth in the coming years due to the strategic advantages they offer to companies.

A study conducted by Goldman Sachs estimates a surge in the XR-related market revenues, up to $95 billion in 2025, with a steady growth oscillating between 58% and 63% since 2016 (as a whole, accounting also for the CAGR related to the hardware technology) [92]. In line with the results of the market reports, a study conducted in 2020 implementing VR and AR can enhance the market share, reputation, and overall performance of a general AEC company, with consequent reduction of costs, improvement of stakeholders' collaboration, and the enhancement of project understanding [32]. Based on these assumptions, Western Michigan University, in collaboration with the University of Alberta, conducted a quantitative-qualitative analysis of articles related to the Virtual Reality-in AEC industry published between 2008 and 2020 to identify the research trends and highlight challenges and opportunities for future implementation studies. The corpus collected accounts for 206 works and provides insights into the potential represented by this technology for the industry's future. Researchers have thus identified six macro-categories or research themes on which XR is expected to have a positive impact in the near future. These mentioned categories concern engineering education, architectural and engineering design, human behavior and perception, construction project management, construction safety, and construction equipment [93]. Furthermore, in even more recent years, the research corpus has witnessed a growth in the direction of the cooperation between XR systems and BIM digital twins, particularly due to the essential role that Building Information Modeling currently possesses in the AEC industry [94]. A seminal work conducted by Northwestern University in 2020 focuses on the topic by studying specifically the cooperation between XR and BIM. In this case, researchers identify and classify the strengths and weaknesses of XR-BIM systems, providing an overview of all the different methods and software currently available in the market to facilitate the implementation of BIM models into VR, AR, or MR scenarios [95]. Even more recently, incremental cooperation between XR systems and BIM digital twins can be noticed due to the essential role they are currently gaining in the AEC industry [94]. Several works have been analyzed and reviewed to provide a strategy to enhance BIM methodologies via the use of Virtual Reality [96][97], while the usability of AR technology on BIM platforms has been largely discussed and analyzed in the literature, in particular consolidating the contributions of this binomial for construction projects [98] and its management [99]. In these cases, one of the major issues for the implementation is represented by the effectiveness of data exchange among the different platforms involved. Extensive work has been produced aiming at finding a generally applicable methodology to ensure effective cross-platform information flow and unify project phases around a Digital Twin [100]. The increasing interest of the AEC sector towards XR-BIM technologies is well represented by the growing number of research works that propose real case-study implementations and field testing [101]. Studies are, in fact, exploring the development of multi-simulation environments that blend cross-disciplinary aspects of the AEC industry[102]. These efforts reflect the growing momentum toward practical applications of XR technologies in real-world scenarios within the AEC sector.

3.4   PREVIOUS WORKS

An initial investigation on similar "hands-on" studies was performed to set the base of this research, investigating five years of contribution for a window spanning between 2016 and 2023 [103]. The decision to include a relatively short time frame derives from the inevitable distancing from the current state of the art of technical and technological solutions tested or implemented during previous years [104]. The pool of investigation was found to be quite limited. In fact, only a corpus of 60 documented works contributes to increasing awareness about the validity of XR-BIM systems in support of the AEC industry via direct project experimentations and implementation (Figure 6).
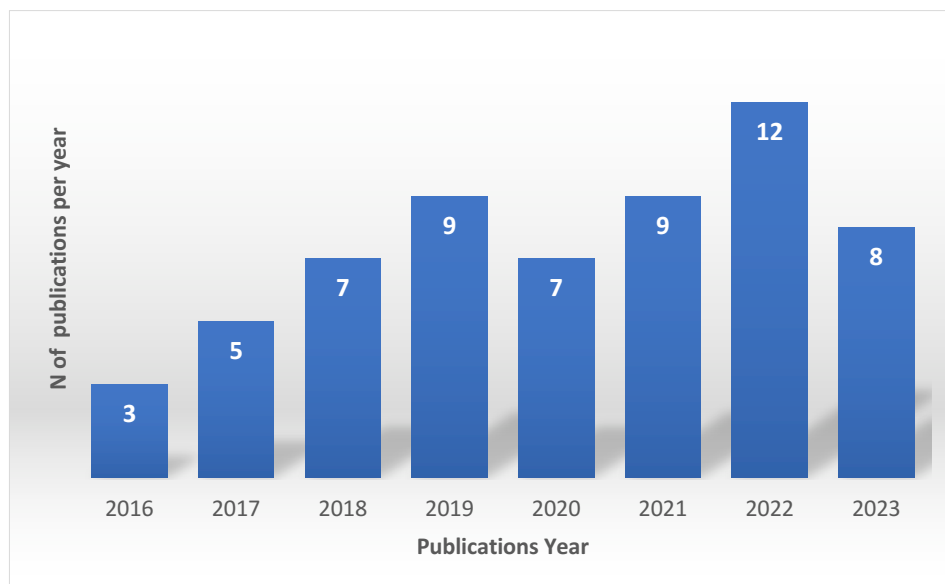
Figure 6 – From [103] *XR-BIM implementations on actual projects between 2016 & 2023.*

These works assessed the contribution of VR, AR, and MR on BIM platforms, in line with the categories proposed by previous studies, which can be overall grouped into four main categories, XR-BIM for Education, XR-BIM for Design, XR-BIM for Construction and XR-BIM for Post-contract.

3.4.1   XR-BIM FOR AEC EDUCATION

The impact of these technologies on education strategies related to the AEC has been the central item of several works in the last few years. Research has been carried out on the existing literature concerning the benefits and challenges of implementing this technology in supporting students' learning curves. In fact, a study conducted by Kırıkkale and Gazi Universities has found that Augmented Reality has the potential to largely improve students' knowledge assimilation of topics related to engineering design and construction [105]. I.e., the work conducted by the Vienna University of Technology aimed at helping students familiarize themselves and get in contact with the reality of the

AEC industry. In this case, an AR-BIM teaching-support system enhances students' AEC educational experience, allowing them to interact directly with professionals, thus transforming the experience into a distance learning session. The researchers demonstrated the usability of their AR-BIM system by using the BIM model of the case study as a platform for the implementation of AR content, such as animation or annotation, and then tested it via two use case applications, a walk through the construction site and an example of on-site clash detection. Participants' feedback demonstrated the proposed system's positive impact, which increased motivation and students' interest [106]. In a similar fashion is the work conducted by the University of Florida, which aims to increase the expertise of the AEC workforce by enhancing the practical skills acquisition process by using AR-BIM platforms. This study simulates the construction assembly context and constraints by superimposing the BIM model elements on-site via AR. The pedagogical benefit of the experience is demonstrated by the test conducted on a low-rise educational and administrative building of the campus, where it was proven that students exposed to the AR-BIM experience could better identify and manage the tasks related to the construction process, compared to their classmates who received standard in-class education [84]. AR is not the only eXtentded Reality system that can support students in their AEC education. The work conducted by Southwest University in collaboration with Curtin University and The Hong Kong Polytechnic University assessed the extent of Virtual Reality's contribution to the matter, particularly in the case of BIM-supported uses for construction engineering education and training, finding that visualization and design creation are the study areas that benefit the most of VR support [107].

The research conducted by Northwestern University about a VR-BIM-enabled is another example of how this technology can support the students' learning curve. In this case, researchers wanted to assess the effectiveness of the proposed system by evaluating its influence on the eight factors that are deemed to affect the learning performances of the students (namely: Learnability, Interoperability, Visualization, Real World, Interaction, Creativity, Motivation, Comfort). The test was conducted on a controlled group of students who visited a high LOD BIM model of the Norris Center building of the Northwestern University campus, using different types of VR HMDs, providing their feedback on the system's validity. The results demonstrated that the VR-BIM tools could provide substantial benefits to the learning experience as they can increase motivation, enhance Visualization, Creativity, and Interaction of students, as well as improve the understanding of real-world scenarios [108].

3.4.2 XR-BIM FOR DESIGN

XR-BIM technologies also provide substantial contributions to the design and planning disciplines. The review conducted by the Technion-Israel Institute of Technology shows the capabilities offered by VR systems to architects and other AEC professionals by helping stakeholders visualize realities that do not yet exist but in the minds of designers [109]. In other cases, such as the research conducted by Aarhus University on an apartment building under construction (by the time of the test) in Norway, the authors applied a VR-BIM system integrated with a Life Cycle Assessment (LCA) software to help stakeholders understand how design choices impact the sustainability and the cost of construction. The authors applied an experimental-qualitative-quantitative method to their research by using a BIM

system as an implementation platform for the LCA software while using VR HMDs to assess the different designs. The researchers used the BIM software to create six different façade solutions and then performed a cost and lifecycle assessment per each alternative, generating a data benchmark to compare with the stakeholders' feedback about the same solutions obtained via VR exploration by focus groups. The experiment's results demonstrated the effectiveness of VR in helping stakeholders understand the impact of their choices on the design towards a sustainable design [110].

Similarly, the University of Hong Kong developed a VR-BIM system aiming at enhancing building energy efficiency in a user-centric way. The researchers implemented a "Design with Intent" strategy using a VR-BIM tool to collect occupancy information and identify the design patterns guiding occupants to behave in the most energy-efficient way. The system, tested on a standard Hong Kong flat, demonstrated the proposed system's validity by identifying the light switches' positioning as the most influential feature in the occupants' lighting control behavior [111]. In a similar predicament is the work performed by the Polytechnic University of Marche, whose researchers developed an MR-BIM system for the enhancement of façade design towards energy efficiency targets and sustainable renovation. The study develops BIM alternatives of an existing building façade, which are then superimposed on the real building via RFID-tag technology. The different options are then energetically, aesthetically, and technically assessed by stakeholders through an MR platform called "On-site Design Analysis and Verification Service" (ODAVS). Using this system, participants from different disciplines can participate in the assessment collaboratively by providing remarks and insights through audio logs. The results of the experimentation, collected via questionnaires and direct feedback, proved the validity of the proposed system in enhancing and facilitating design choices starting from stakeholders' on-site assessments [112].

XR-BIM binomial provides an important contribution to the AEC industry, helping assess human behavior and perception, leading to better and more efficient design solutions, as demonstrated by the study conducted by the University of Singapore and the Tianjin University on a modular housing building in central Singapore. Researchers applied a VR-BIM system that contributed to the design process by helping optimize indoor comfort. After virtually re-creating the surroundings of the building complex, the researchers applied a computational fluid dynamic simulation on the BIM model of the project and then visually explored the data in VR. The information generated helped the designers to understand better the spaces and volumes concerning the project, leading to the improvement of the design solution [113]. Another instance concerns the test conducted by The University of Osaka about the manipulation of and interaction with BIM lighting systems and the visualization of lighting phenomena (e.g., glare) through a VR headset to enhance the lighting design of the project and, consequently, the perceived internal comfort. Starting from the model of a pre-selected office (on the fourth floor of the M3 building of the campus), researchers developed a BIM-based lighting design feedback system helping designers experience the lighting quality of their project and assess the energy consumption of the proposed solutions in an immersive and interactive environment. The direct experimentation of the proposed system in the office resulted in the validation of the tool, which can provide a holistic and

faithful overview of the lighting solutions, therefore generating useful feedback to improve the design [114]. The work conducted by the researchers of Perugia University is another example of VR-BIM collaboration for design development based on human behavior analysis. The researchers propose a new analysis framework to better understand people's environmental perception since the early design stages. This work used three non-thermal parameters (windows aspect ratio, artificial light color temperature, and glass filter films) to solicit participants' responses to the virtual environment thermal change while VR-experiencing a BIM replica of an existing university office. The feedback that followed showed a perceived "placebo" effect on the participants, thus demonstrating the validity of the proposed system in supporting the design stages by producing human-centric energy-efficiency enhancement and reducing future costs [115]. VR-BIM systems can also be used to simulate crowded conditions and internal personnel flows to support design decisions, as demonstrated by a case study where the researchers translated post-occupancy evaluation data into a dynamic simulation and applied it to the BIM model of an existing hospital pavilion. The users' feedback collected during the VR experience was later used to assess potential pavilion interior layout reconfigurations, thus proving the system's validity in support of the design [116]. VR can be successfully used on BIM platforms to perform MEP clash detection, as the practical experiment conducted by Tianjin University demonstrates. During the design stages, the researchers conducted a series of "MEP virtual inspections" on the BIM model of a 3000 m2 project to identify pipes' collision issues otherwise not noticeable on 2D drawings of the same. The information collected was then used to refine the MEP layout from the early design stages, thus helping deliver a better-engineered project [117].

3.4.3 XR-BIM FOR CONSTRUCTION
Communication and stakeholders' engagement are two project management pillars, and, as stated before, XR-BIM systems represent a great asset to the topic, specifically with respect to the AEC domain [118]. The Chalmers University of Technology tested the effectiveness of a VR-BIM system for design coordination, decision-making, and construction planning for an actual office building. The researchers approached stakeholders involved in the different design stages and had them "visit" the BIM model of the building using a VR headset and collected their feedback on the validity of the proposed system for communicating and experiencing the design intents of the project. The result concluded that "the VR on the BIM platform can facilitate better-shared perceptions, interpretation and understanding of the design problem in the design team" [119]. The work conducted by Monash University in Melbourne is also about stakeholders' involvement and focuses particularly on empirically measuring the effectiveness of VR-BIM systems for team coordination. The study uses the Charette Test method to compare the traditional 2D-based design coordination session with an enhanced BIM-VR experience in the case of a design renovation of the one-level mechanical lab in Building 4 of the Monash University campus. Specifically, the first approach involved the visual inspection of multiple 2D computer-aided design (CAD) drawings, while the second entailed the visual inspection of three-dimensional (3D) building information modeling (BIM)-based virtual reality (VR) models. The experimental findings unequivocally demonstrated that the application of VR technology not only expedited the detection of clashes but

also enhanced the accuracy and utility of the identification process. Therefore, these outcomes underscore the potential of BIM-based VR technology as an efficient and effective tool for facilitating clash detection and mitigating potential construction issues [120]. Information and its coordination are key elements for design review and increasing the information access efficiency and speed results in improved management processes. The Texas A&M University, in liaison with the researchers of the Michigan State University, developed a VR-BIM system automating the data transfer from BIM platforms to VR systems, thus providing real-time synchronization via a Cloud BIM metadata interpretation and communication protocol. The system, named BVRS, virtually cancels the time interval necessary to process BIM information for VR implementation, thus basically removing the related workflow. This "zero-latency communication protocol" was experimented on the Francis Hall building at Texas A&M University and proved its validity by maintaining the fidelity of design data, undisruptive design changes synchronization, and high compliance with the original material information in BIM authoring tools [121], [122].

Stakeholders' involvement in the design process is, in fact, essential for the successful delivery of the project, and immersive technologies can facilitate the communication of design intent to all parties and help in managing the information exchange. The researchers of the Universitas Politècnica de Catalunya implemented in their case study (the "Campus Generalitat" building by CT Engineer) a collaborative workflow based on a VR-BIM system for both the MEP and the Architecture disciplines. The participants had to perform tasks in a virtual environment onto a federated BIM model and experienced a series of design coordination and review meetings, followed by a clash detection session, which ended in a presentation to stakeholders, thus simulating a typical design team workflow. During the simulations, important feedback was given on how to address workflow implementation weak points (e.g., maximum VR immersion time should not exceed 20 minutes per session). The results demonstrated the positive impact of this technology on the existing workflow by enhancing the ability of the participants to recognize and solve clashes that might have occurred on-site without affecting the regular workflow of the project development [123].

The construction phase can also largely benefit from the implementation of XR on BIM, and numerous studies have already discussed the contribution that these systems can deliver by highlighting the support that Augmented Reality provides both from a conceptual and practical standpoint [124]. An example is the research conducted by the University of Bozen, where the authors implemented a tablet-based AR-BIM app called AR4C, allowing for data gathering concerning the status of the site's progress and returning information about productivity, work quality, and project schedule via a virtual dashboard. The system relies on the BIM digital twin of the building, which is superimposed on the site, and it works as an information repository, thus allowing users to access relevant data for work progress management. By the time of this review, the tool was tested on a 200 m2 site in Bozen (IT) to verify and improve the precision of the BIM-model alignment with the site. At the same time, planning was made to implement system components to read construction progress and let users see the construction performance through colored visual KPIs [125]. Arizona State University conducted a similar study on a

proof of concept that tested an MR-BIM system for the comparison of "as-built" drawings with the actual constructed condition. The research specifically tested the usability of immersive AR (Mixed Reality) as a tool for identifying construction deviations in the MEP systems. Users inspected a corridor plenum in one of the buildings on the University campus by using its BIM model as a virtual comparison. The aim was to prove the effectiveness of the proposed system in highlighting possible discrepancies to correct the final BIM model before the turnover of the completed building and thus facilitate building management during operation. The results demonstrated that MR-BIM could help users effectively identify large deviations or missing project elements, but it is still not precise enough to substitute more resource-intensive and reality-capturing technologies (like laser mapping) for detailed deviation detections [126]. The cooperation between XR and BIM can greatly improve the work efficiency on site, as demonstrated by the researchers of Curtin University in Australia, who aimed to integrate AR onto a BIM platform to improve construction workers' productivity by enhancing their ability to retrieve information on-site. A design science research approach was used for this work, which enriches ordinary 2D paper-based construction drawings with referenced QR codes, allowing for on-site retrieval and visualization of cloud-stored BIM information. The results of the study demonstrated that the use of this AR-BIM system improved workers' efficiency by 50% by increasing their task completion speed and reducing the likelihood of errors [127]. Similarly, ShoP Design's case study in New York proved the validity of AR on a BIM platform to support site surveys and ease information flow between the site and the design office. The main goal of the study was to demonstrate the usability of AR as a substitute for conventional 2D construction drawings. Researchers used QR markers to pin the BIM model on the case study and leveraged the information contained in the model to allow contractors to understand design intent directly on-site more quickly and comprehensively. Workers could access all drawings concerning specific building elements by selecting them via the mobile-operated AR app that is used to project the BIM model onto the physical environment. In doing so, the contractor's workforce could minimize the time spent searching and cross-referencing construction drawings, therefore leading to increased on-site productivity and fewer mistakes [128]. Similarly, the proof of concept developed by the researchers at Arizona State University aimed to verify the validity of an MR-BIM tool in substitution of 2D drawings for the on-site installation of MEP conduits. The research aimed to verify how the proposed system influences the productivity and quality of electrical conduit construction against standard practice. The study's results showed the performance benefits of using the MR-BIM system in terms of quality and task completion time. Specifically, it was demonstrated that workers with no assembly experience reached correct task completion faster than the most experienced participants with traditional 2D drawings [129]. The Chalmers University of Technology conducted another test on a VR-BIM system aiming primarily at facilitating workers' understanding of the site production needs while enhancing their perception of the project and easing data retrieval. The system was tested on the construction site of a bridge in Sweden, and it allows workers to easily navigate and inspect the BIM twin of the project by providing the capability to take measurements and place 3D data-rich labels directly on the BIM model. The production-oriented information generated during the virtual inspection can be collected as snapshots and distributed via the cloud to other workers on-site, who can access

it via tablet or mobile. The result of the experimentation proves the effectiveness of the system in helping workers to better understand the overall picture of the project and its production needs compared to regular 2D drawings [130]. In the same predicament, the University of Bozen-Bolzano addresses the implementation of MR-BIM platforms to support on-site MEP workers by aiming to reduce execution time and increase performance quality. The researchers used an Italian multistory apartment building under construction as a case study to test the MR-BIM system for marking and installing MEP conduits. The results showed a construction time saving between 39.3% and 84% compared with standard methods and an overall total deviation between 2 and 8 cm compared to final design positioning [131].

Another key item that has been thoroughly discussed in the literature is the support that XR-BIM systems can provide for safety on construction sites [132]. Safety on the building site is a particularly important topic in the AEC industry, and the cooperation between XR technologies and BIM can contribute to improving it [133]. The proof of concept presented by the researchers of the University of Paris Saclay Guyancourt aims to demonstrate that XR-BIM platforms can have a solid impact on on-site safety training. Workers took part in a workshop about site procedures through Virtual Reality by using the BIM model of the site as a training environment to learn beforehand how to properly plant, handle, and stabilize large concrete formworks. Workers in VR were guided through the same steps as they would have then repeated in real life, thus helping them understand possible difficulties and preparing them for the actual site. The feedback obtained was overall positive, although it was highlighted that a better ergonomics simulation might have increased the effectiveness of the tested tool [87].

Similarly, the University of Auburn tested a VR-BIM system for site safety planning and workers' safety training during the renovation of one of the buildings on the campus. In this case, the researchers developed a BIM digital twin of the construction site that depicted the renovation of the building at different stages and implemented equipment, cranes, vehicles, and other construction-related items to simulate different site scenarios. Workers experienced the virtual environment through VR headsets and approached different hazardous scenarios created specifically for safety training (e.g., use of forklift, electrical hazards, inadequate fall protections), thus providing feedback on the system's usefulness and effectiveness. The test result confirmed the VR-BIM system's potential to enhance training on construction-site safety [88]. Another crucial aspect of on-site work is construction safety management. The United Arab Emirates University approached this topic via a case study in Al Ain, Abu Dhabi (UAE), characterized (as most of the building sites in the MENA region) by a multi-cultural and multi-language mix of workers. The heterogeneous environment of this research is relevant, as managing situations involving people from different world regions and speaking different languages is particularly challenging. Thus, a multi-language 4D BIM-VR system is tested on-site to facilitate risk assessment and help with hazard identification and safety training. The system, tested on a construction site in Al Ain, provides each workforce layer (from the site manager to the site worker) with immersive safety training exercises based on the initial experts' assessments of the risks-mitigation plan. The results showed a significant improvement in the site crew's ability to recognize a hazard,

understand safety protocols, and incorporate proactive risk response, ultimately allowing site managers to communicate and coordinate better with workers and easing the on-site safety procedures management [90].

XR-BIM systems also prove effective as a support tool for equipment and material management on the construction site, as demonstrated by the work conducted on a Chinese power plant by the researchers of the North China Electric Power University. In this case, an AR-BIM platform was tested to provide visual guidance and support for outbound tracking, stacking, and inventory controlling of construction materials via a tablet-operated app. The system used AR to overlap the BIM model containing material management information onto the site while providing collaborative features to verify and control the status of the site materials. The result of this experiment showed an increase in the efficiency of material handling and acceptance while reducing the risk of accidents caused by non-standard stacking of materials [134]. XR-BIM systems can be used to enhance construction aspects via "design-like" tools. I.e., the research conducted by the University of Pisa in collaboration with the University of Negev aimed to assess the validity of VR technology on the BIM platform as a tool for supporting construction site planning. The authors simulated the work environment by using BIM software, and the workers experienced the virtual site conditions via VR. The feedback collected generated a new configuration of workspaces in the construction plan that was validated on the building site of an office building extension in Pisa (IT). The study demonstrated the validity of the BIM-VR system in improving construction activity workspace planning by facilitating the sharing of safety-related information between partners [135]. Of a similar predicament is the study conducted by the researchers of the Eastern Mediterranean University, in liaison with the Northwestern University, the Eastern Mediterranean University, and the Jönköping University, which aimed to corroborate the validity of VR-BIM system to enhance the construction site layout and planning. Two different BIM models are generated based on the construction plot parameters, one representing the actual building site scenario and the other one providing variations and alternative solutions to the "site points of interest" (e.g., location of the site office, parking areas, equipment location, crane placement, material locations, trash waste access, and a stockpile of excavated soil). The test participants experienced both models through VR and were asked to provide feedback concerning their understanding of site conditions and their perception of site criticalities against the 2D representation of the same site. The data collected through questionnaires and direct observation demonstrated that the proposed VR-BIM system could enhance construction site layout planning as well as increase site criticality awareness compared to the standard 2D representations [136].

3.4.4   XR-BIM FOR POST-CONTRACT

Design and construction are not the only phases of the building life cycle that can benefit from the support of the XR-BIM binomial. As further studies highlighted, the post-construction stage can also take advantage of VR and AR technologies, which provide great support to building operation and maintenance [137]. Facility management can also benefit from the implementation of XR technologies

on BIM platforms. The system proposed by the Concordia University researchers aims to support and facilitate field tasks, tracking and monitoring their completion via real-time collaboration between the office and the site. The field worker receives remote AR GPS-based instructions from the manager who is in the office and interacts remotely via an MR-BIM system. The implementation of the tool in the management of building operations was tested on the Engineering and Visual Arts Building of the campus system and demonstrated the validity of this technology in supporting work management, thus resulting in a reduction of the task completion time by 85%, and of the chance of errors by 65% compared to standard methods [138]. The XR-BIM collaboration in support of best practice procedures during the building operation phase also includes the test conducted on an office building in Tianjin (CH), where a crowdsourcing VR-BIM application called "iInspect" is used in tandem with an indoor-localization system to provide fire safety and fire-fighting reporting to the competent authority, aimed at ensuring building compliance with the fire code. The system developed by the researchers of Tianjin University uses GPS coordinates to determine which premises users are currently present and delivers VR fire-safety information about the building via its cloud-based data-rich BIM-twin. The user can digitally access the templated survey in the form of a checklist, fill it in with useful information, upload relevant pictures, and crosscheck the work of previous users. The collected information is then stored in the BIM model and remotely verified by the off-site fire safety managers [139]. XR-BIM technologies can support not only the management of the building but also its landscape, as demonstrated by the research proposed by the Beijing University of Technology. In this case, the researchers developed a framework based on BIM-MR cooperation, which set out to facilitate the maintenance of large landscape projects by creating and manipulating its virtual twin. The study uses a multi-user collaborative Mixed Reality environment to visualize and operate on the spatiotemporal data of dynamic BIM models of the project plant species in real-time. The virtual placement of the data-rich model of the plants is determined through the mapping of the virtual anchor point in the platform and the landmark point in the real scene, while the plants' relevant information (geometric, botanical, and maintenance) is stored as component attributes which can be easily accessed via MR. The test results conducted on Jinhu Park demonstrated the validity of the proposed system in supporting the plantation and maintenance of the park greenery while ensuring sustainable landscape ecology [140].

4 ENTITIES, MATERIALS, AND METHOD

4.1 ENTITIES

This work, which aims to provide support for the development of proprietary software, has been conducted using a case study, which was under construction at the time this thesis was written. The project, used as a testing ground for the VR application, was designed in close collaboration with numerous entities. A brief overview of the major external parties involved with this research might be useful to frame the research work.

4.1.1 DESIGNERS

The architectural design of the project was formulated by "MMAprojects Srl", an Italian architecture and interior design company founded in 1999 and based in Milan with a large portfolio of residential and hospitality projects in Europe, Asia, and the Middle East [141]. "Dynamic Design Studio" is an engineering company founded in 1995 and based in Dubai with a proven large experience in the structure field (most notably the Royal Atlantis Dubai and Warner Bros World Dubai), which is responsible for the structural consideration and design of the project [142]. "Nottingham ME Consulting" is a company founded in 2005 and specializes in the United Arab Emirates MEP regulation that designed the MEP system of the building [143]. Finally, the interior design of the entire building has been developed by the Parisian company "AM Interior Design", founded in 2008 and specialized in luxury and extra luxury interiors, such as the two M Gallery hotels and a five stars Sofitel Doha in Qatar [144].

4.1.2 DEVELOPERS

Khamas Group of Investment Co's (L.L.C)'s (L.L.C). is a long-standing enterprise in the United Arab Emirates, established in the early 1980s. The group has a significant presence in construction and various other industries, comprising over 120 enterprises within the Emirates. Its reputation extends globally, supported by its diversified Divisions, including Developments, Contracting and construction, Hotels, Hospitality, FMCG, Manufacturing, Franchising, and Education. The group is staffed with a highly qualified and experienced workforce and operates both in the UAE and international markets, currently employing more than 10,000 individuals. Projections indicate further workforce expansion in line with the group's growth strategy. The success of Khamas Group is attributed to effective divisional leadership, the expertise of its dedicated workforce, and its commitment to fair business practices, even amid intense competition. Throughout its extensive history, Khamas Group has earned a reputable position as a trusted institution known for its accomplishments across various industries in the UAE [145].

4.1.3 SOFTWARE PROVIDER & DEVELOPER

The software house that actively collaborated with the research, and for which the research results are intended to be contributive, is the Italian company ACCA Software. Founded in 1989 by Guido Cianciulli,

ACCA is the company with the largest number of IFC-certified BIM software solutions in the world, and it is entirely dedicated to the development and implementation of software for the AEC industry. It provides a total of 120 proprietary applications for industry professionals, which brought the company to occupy a leading role in the European market. Furthermore, the declared company mission of seeking the implementation of openBIM strategies in all its products has made the company an active member of buildingSMART® Multinational [146] in Europe.

4.2   MATERIALS

Because of the "hands-on" and experimental nature of this research, the materials applied for the development of the study list as a specific set of hardware and software components, aside from the project case study onto which the research work was conducted. The description of both the hardware and the software implemented for this research is relevant to understanding the work performed and its outcome. As previously explained, the software (in Beta version) used for this research is proprietary to ACCA Software, which issued a beta-testing license for its application, granting full access to all implemented software features (up to date). Although neither programming nor coding works are the subject of this research, providing an overall panoramic of the software helps to understand the analysis of the data collected. On the other hand, the hardware selection and subsequent research implementation underwent a process of trial and error that generated two radically different setups, only one of which was successful and allowed for software operability and testing. During a detailed exchange with the R&D department of ACCA Software, information was collected concerning the minimum Hardware requirements in terms of both the Computation Processor Unit (CPU) and Graphic Processor Unit (GPU) for the installation and implementation of the usBIM.reality software. The relevance of the hardware specs description and their comparison with the recommendations received from ACCA Software lies in the importance of the initial software implementation failure from a developing standpoint, as it might allow future releases to overcome the obstacles encountered. The selection of the Head Mounted Display (HMD) also represents an important step for the research due to its specifications, which shall be taken into consideration when testing the operability of the software, as they might have an impact on the research outcome. Finally, the high-level description of the case study is important to provide context to the operations performed in the virtual environment during the tests.

4.2.1   ACCA Software CPU RECOMMENDATIONS & CPU COMPARISONS

According to the information provided by ACCA Software technical department, an optimal CPU approach for the hardware setup was the AMD Ryzen 9 series, specifically the 6900HS model [147]. This Chipset processor (Figure 7), unveiled in January 2022, employs the Zen 3+ (Rembrandt) architecture, utilizing Socket FP7. Leveraging AMD Simultaneous Multithreading (SMT), the core count effectively doubles to accommodate 16 threads. The default clock speed of the Ryzen 9 6900HX is 3.3 GHz, with the

potential for boosting up to 4.9 GHz, depending on the workload. The processor supports DDR5 memory through a dual-channel interface, with the highest officially endorsed memory speed at 4800 MHz and even the potential for higher speeds with overclocking of compatible memory modules. Communication with other system components occurs via a PCI-Express Gen 4 connection, and it presents the Radeon 680M as an integrated graphics solution. The processor also accommodates programs utilizing Advanced Vector Extensions (AVX), providing a performance boost for calculation-intensive applications. In addition to AVX, the Ryzen 9 6900HX includes the AVX2 standard, omitting AVX-512 support [148].

General Specification	
Platform	Boxed Processor
Product Family	AMD Ryzen Processors
Product Line	AMD Ryzen 9 Desktop Processors
Former Codename	"Vermeer"
# of CPU Cores	12
# of Threads	24
Max. Boost Clock	Up to 4.8Ghz
Base Clock	3.7GHz
L2 Cache	6MB
L3 Cache	64MB
Default TDP	105W
Processor Technology for CPU cores	TSMC 7nm FinFET
Unlocked for Overclocking	YES
CPU Socket	AM4
Thermal Solution (PIB)	Not included
Recommended Cooler	Liquid cooler recommended for optimal performance
Max. Operating Temperature	90º C
Launch Date	11/5/20
OS Support	Windows 10 - 64-Bit Edition
	RHEK x86 64-Bit
	Ubuntu x86 64-Bit

Figure 7 – Vermeer General specs.

ACCA Software developers also recommended alternatives to the AMD technology in the form of two CPU options: the Intel® Core™ i7-12700HL, code name "Alder Lake-H" [149], and the Intel® Core™ i9-12900 "Tiger Lake-S" [150]. The first one (Figure 8), introduced in January 2022, operates based on the Alder Lake-H architecture with a Ball Grid Array (BGA) of 1744 and a total of 14 cores, which are effectively doubled thanks to the use of Intel Hyper-Threading technology, resulting in 20 threads. The default clock speed for the Core i7-12700H is 2.3 GHz, although it can reach a maximum boost frequency of 4.7 GHz. This Intel processor supports both DDR4 and DDR5 Memory, utilizing a dual-channel interface. Communication with other hardware components is facilitated through a PCI-Express Gen 4

connection, and in terms of graphic power, the Intel® Core™ i7-12700HL incorporates the Iris Xe 96EU integrated graphics solution. The Core i7-12700H presents hardware virtualization capabilities, which significantly heightens the performance of virtual machines. This processor, in fact, supports the input–output memory management unit (IOMMU) virtualization, which grants the ability for guest virtual machines to access host hardware directly. Furthermore, applications utilizing Advanced Vector Extensions (AVX) are compatible with this processor, effectively amplifying performance for computationally intensive tasks. In addition to AVX, Intel has incorporated support for the newer AVX2 standard, though AVX-512 is not included [151].

General Specification	
Product Collection	12th Generation Intel® Core™ i7 Processors
Code Name	"Alder Lake"
Vertical Segment	Embedded
Processor Number	i7-12700HL
Use Conditions	PC/Client/Tablet
Total Cores	14
# of Performance-cores	6
# of Efficient-cores	8
Total Threads	20
Max Turbo Frequency	4.70 GHz
Intel® Turbo Boost Max Technology 3.0 Frequency ‡	4.70 GHz
Performance-core Max Turbo Frequency	4.70 GHz
Efficient-core Max Turbo Frequency	3.50 GHz
Processor Base Frequency	2.30 GHz
Cache	24 MB Intel® Smart Cache
Processor Base Power	45 W
Minimum Assured Power	35 W
Maximum Assured Power	65 W
Marketing Status	Launched
Launch Date	Q3'22
Max Memory Size (dependent on memory type)	64 GB
Memory Types	Up to DDR5 4800 MT/s Up to DDR4 3200 MT/s
Max # of Memory Channels	2

Figure 8 – Alder Lake general specs.

The second alternative to the AMD CPU is also part of the Intel® Core™ lineup (Figure 9). Thus, very similar solutions to the ones implemented onto the i-7 can also be found on the Intel® Core™ i9-12900. Like the i-7, the i-9 is a processor based on Alder Lake-S architecture with Socket 1700 that presents 16 cores, effectively doubled thanks to Intel Hyper-Threading to 24 threads. The i9-12900 has 30MB of L3 cache and operates at 2.4 GHz by default but can boost up to 5.1 GHz, depending on the workload. Like the i-7, the Intel® Core™ 9-12900   supports DDR4 and DDR5 Memory with a dual-channel interface. For

communication with other computer components, the i9-12900 uses a PCI-Express Gen 5 connection, and it hosts the UHD Graphics 770 (Alder Lake) integrated graphics solution.

Similarly, to the i-7, the i-9 also offers hardware virtualization and IOMMU for better virtual machine performances via host hardware. Finally, the processor presents support for Advanced Vector Extensions (AVX), AVX2, and AVX-512 technologies [152]. The three suggested solutions do not differ enormously from each other, as shown in Table 1, but for the regular clock speed and the MB capacity for the Cache level. Provided that the ACCA Software developers clearly stated the equivalence among the hardware systems, the selection of the CPU for the research fell on the Intel® products due to lower acquisition cost and quicker availability (by the time this research started).

General Specification	
Product Collection	12th Generation Intel® Core™ i9 Processors
Code Name	Tiger Lake
Vertical Segment	Mobile
Processor Number	i9-12900H
Lithography	Intel 7
Total Cores	14
# of Performance-cores	6
# of Efficient-cores	8
Total Threads	20
Max Turbo Frequency	5.00 GHz
Intel® Turbo Boost Max Technology 3.0 Frequency ‡	5.00 GHz
Performance-core Max Turbo Frequency	5.00 GHz
Efficient-core Max Turbo Frequency	3.80 GHz
Cache	24 MB Intel® Smart Cache
Processor Base Power	45 W
Maximum Turbo Power	115 W
Minimum Assured Power	35 W
Marketing Status	Launched
Launch Date	Q1'22
Embedded Options Available	No
Max Memory Size (dependent on memory type)	64 GB
Memory Types	Up to DDR5 4800 MT/s Up to DDR4 3200 MT/s Up to LPDDR5 5200 MT/s Up to LPDDR4x 4267 MT/s
Max # of Memory Channels	2

Figure 9 – Tiger Lake General specs.

Two Intel® Core™ CPUs were implemented (one after the other) on the research, based on the recommendations received and the funds availability. The first instance is the Intel® Core™ i7-1068NG7 "Ice Lake" [153], which falls within the Core i7 family and is built upon the Sunny Cove-U architecture utilizing BGA 1526. Through the utilization of Intel Hyper-Threading, the initial 4 cores core count is effectively enhanced to 8 threads. It incorporates 8MB of L3 cache and maintains a base clock of 2.3

GHz, with the capacity to turbo boost up to 4.1 GHz. The Core i7-1068NG7 is equipped with a locked multiplier, limiting its potential for overclocking and, drawing a mere 28 W for its TDP, the Core i7-1068NG7 stands as an energy-efficient solution.

	AMD Ryzen 9 6900HS Creator Edition	Intel Core i7-12700H Alder Lake-H	Intel Core i9-12900 Tiger Lake-S
Socket Type	FP7	FCLGA1700	FCBGAI 744
CPU Class	Laptop	Laptop	Desktop
Clock speed	3.3 GHz	2.3 GHz	2.4 GHz
Turbo Speed	Up to 4.9 GHz	Up to 4.7 GHz	Up to 5.1 GHz
RAM Type	DDR5	DDR4	DDR4 & DDR5
# of Physical Cores	8 (Threads: 16)	14 (Threads: 20)	16 (Threads: 24)
PCI-Express	Gen 4	Gen 4	Gen 5
Cache	L1: 512KB L2: 4.0MB L3: 16MB	L1: 768KB L2: 4.0MB L3: 24MB	L1: 768KB L2: 4.0MB L3: 30MB
Integrated GPU IOMMU	AMD Radeon 680M Yes	Intel Iris Xe Graphics Yes	Intel UHD Graphics 770 Yes

Table 1 - AMD & Intel CPU breakdown.

This Intel processor supports DDR4 memory and employs a dual-channel interface with the highest declared memory speed reaching 3200 MHz. It uses a PCI-Express Gen 3 connection to communicate with other system components, and from a graphic standpoint, the i7-1068NG7 implements the Iris Plus integrated graphics solution. Hardware virtualization and IOMMU are available on the Core i7-1068NG7, which also enables programs using Advanced Vector Extensions AVX, AVX2, and AVX-512 instructions [154]. The overall power and performance capabilities of the first system appear somewhat lower than the recommended counterpart, the Intel® Core™ i7-12700H (Table 2). The main differences between the "category-CPU" recommended by ACCA Software and the one tested lay in the number of Cores, 4 for the latest against the 14 of the recommended one, and Cache capabilities, 24MB on level 3 for the i7-12700HL and only 8MB for the same level in the case of the tested system.

Furthermore, additional differences can be found in the technology for communication with additional hardware components. The "Ice Lake" CPU implements a PCI-Express Gen 3 type of connection, while the "Alder Lake-H" presents PCI-Express Gen 4 technology, providing virtually double the bandwidth for data transfer. The two most relevant features for the intent of the research, Clock speed, and Memory type, remain the same in both instances, presenting a frequency of 2.3 GHz and compatibility with the DDR4 memory type.

The second tested processor aligns more closely with the received specifications when compared to the first tested solution. Specifically, the Intel® Core™ i9-11900KB "Tiger Lake" [155] stands in the Core i9 series, and it embraces the Tiger Lake-H architecture through the BGA 1787 interface. Notably, its

configuration allows for achieving a 24MB L3 cache, while default operation sustains a clock speed of 3.3 GHz, albeit with the potential for boosting up to 4.9 GHz contingent upon the computational workload. Profiting from the Intel Hyper-Threading technology, this processor augments the initial count of 8 cores to an effective tally of 16 threads. Furthermore, Intel endows this CPU with the flexibility to adjust the unlocked multiplier freely, significantly simplifying the process of overclocking by enabling manual frequency alteration. The Core i9-11900KB integrates DDR4 memory through a dual-channel interface, with an official top memory speed of 3200 MHz and the option of achieving even higher speeds through overclocking. In terms of inter-component communication, the Core i9-11900KB uses a PCI-Express Gen 4 connection, concurrently embodying the UHD Graphics 750 integrated graphics solution. Remaining consistent with the Intel® Core™ lineage, the processor comprehends hardware virtualization, augmented by the presence of IOMMU technology. Furthermore, the processor extends support for AVX, AVX2, and AVX-512 instructions [156]. The power and performance capabilities of the i9-11900KB are much closer to the specs suggested with the i9-12900 than the i7-1068NG7 is with the i7-12700H (Table 2). The i9-11900KB easily tops the recommended clock speed, offering 3.3 GHz frequency in normal workload conditions, although presenting lower Threads (16 against 24), and it achieves the 24MB Chace in L3 while fully supporting the DDR4 memory type. The only major differences between the two PCUs can be found in the technology for inter-components communication, PCI-Express Gen 4 in the case of the tested system against the Gen-5 of the Tiger Lake-s, and the number of Cores, 16 for the ACCA Software recommended processors and "only" 8 for the tested one.

	Intel Core i7-12700H Alder Lake-H	Intel Core i7-1068NG7 Ice Lake		Intel Core i9-12900 Tiger Lake-S	Intel Core i9-11900KB Tiger Lake
Socket Type	FCLGA1700	FCBGA1344		FCBGAI 744	FCBGA1787
CPU Class	Laptop	Laptop		Desktop	Desktop
Clock speed	2.3 GHz	2.3 GHz		2.4 GHz	3.3 GHz
Turbo Speed	Up to 4.7 GHz	Up to 4.1 GHz		Up to 5.1 GHz	Up to 4.9 GHz
RAM Type	DDR4	DDR4		DDR4 & DDR5	DDR4
Cores	14 (Threads: 20)	4 (Threads: 8)		16 (Threads: 24)	8 (Threads: 16)
PCI-Express	Gen 4	Gen 4		Gen 5	Gen 4
Cache	L1: 768KB L2: 4.0MB L3: 24MB	L1: 320KB L2: 2.0MB L3: 8MB		L1: 768KB L2: 4.0MB L3: 30MB	L1: 768KB L2: 4.0MB L3: 30MB
Integrated GPU IOMMU	Intel Iris Xe Graphics Yes	Intel Iris Xe Graphics Yes		Intel UHD Graphics 770 Yes	Intel UHD Graphics for 11th gen Intel CPU Yes

Table 2 – CPUs Acca Recommendations against Implementations.

4.2.2 ACCA Software GPU RECOMMENDATIONS & GPU COMPARISONS

In terms of Graphic Processor Unit, the recommendation received from ACCA Software R&D department addressed the implementation of minimum specs in the form of either the NVIDIA GeForce RTX 2070 [157] or the AMD Radeon RX 6700 [158].

The first GPU is a high-end graphics card introduced on the market by NVIDIA in October 2018. Founded upon the TU106 graphics processor (Specifically the TU106-400A-A1), this graphics card presents compatibility with DirectX 12 Ultimate, which guarantees the seamless operability of high-end graphic software. Furthermore, the incorporation of DirectX 12 Ultimate supports hardware-raytracing and variable-rate shading, empowering the "video game-like" performances of VR software. Notably, the integration of 288 tensor cores contributes to the acceleration of machine learning applications, while 36 raytracing acceleration cores further amplify the card's capabilities, offering 2304 shading units. The GeForce RTX 2070 integrates an 8 GB GDDR6 memory module harnessed via a 256-bit memory interface.

Furthermore, it incorporates diverse display outputs comprising 1x DVI, 1x HDMI 2.0, 2x DisplayPort 1.4a, and 1x USB Type-C. Implementing connectivity through a PCI-Express 3.0 x16 interface, the NVIDIA GeForce RTX 2070 establishes a nexus with the broader system architecture. This GPU is a dual-slot card measuring 229 mm x 113 mm x 35 mm and integrates a dual-slot cooling solution while drawing power through a singular 8-pin power connector, with a maximal power draw rated at 175 W [159].

The second minimum requirement GPU, suggested by ACCA Software is the Radeon RX 6700. It is a graphics card by AMD, launched in June 2021, and based on the Navi 22 graphics processor (specifically its 22 XTL variant) that supports DirectX 12 Ultimate. As for the NVIDIA GeForce RTX 2070, the GPU compatibility with the DirectX 12 Ultimate allows for hardware-raytracing and variable-rate shading that facilitate the work of the card on VR software. The card has 36 raytracing acceleration cores, offering 2304 shading units, and is paired with 10 GB GDDR6 memory, which is connected using a 160-bit memory interface and PCI-Express 4.0 x16 technology. Being a dual-slot card, the AMD Radeon RX 6700 is a dual-slot card that presents different display outputs, namely 1x HDMI 2.1 and 3x DisplayPort 1.4a, and it draws power from 1x 8-pin power connector, with a power draw rated at 175 W maximum. The card's dimensions are 267 mm x 110 mm x 40 mm, and it features a dual-slot cooling solution [160].

The GPU selection for the research implementation followed a series of considerations, which were not limited to the market availability and acquisition costs of the up-to-specification cards from both fabless companies. The other discriminant was the CUDA® cores framework proprietary of NVIDIA [161], which technology was preferred over the Stream Processor technology of AMD since it is widely credited as a better support system for Machine Learning algorithms.

Thus, NIVIDA products were selected over AMD in light of potential (although later discarded) ML developments or implementations within the research (Table 3).

	NVIDIA GeForce RTX 2070	AMD Radeon RX 6700
GPU	TU106-400A-A1	Navi 22 XTL
GPU Class	Dual slot	Dual slot
Cooling	Dual slot	Dual slot
GRAM	8 GB	10 GB
GRAM Type	GDDR6	GDDR6
RT Cores	36	36
PCI-Express	3.0 x16	4.0 x16
SU	2304	2304
DirectX	12 Ultimate	12 Ultimate
M.L. Tech.	CUDA® cores	Stream Processor
Dimensions mm	L: 229 | W: 113 | H: 35	L: 267 | W: 110 | H: 40

Table 3 – AMD & NVIDIA recommended GPU breakdown.

Two different Nvidia GPUs have been implemented (Table 4), one after the other, during the data collection process. The first graphic card is the Aorus Nvidia GeForce RTX™ 3070 Master 8G [162], launched in September 2020 and based on the GA104 graphic processor that fully supports DirectX 12 Ultimate. As it has been previously described, the DirectX12 Ultimate facilitates hardware-raytracing and variable-rate shading, greatly aiding the work of the card on VR software. The card has 46 raytracing acceleration cores and offers 5888 shading units.

The GeForce RTX™ 3070 Master 8G is paired with 8 GB GDDR6 memory, connected via a 256-bit memory interface, and it is compatible with PCI-Express 4.0 x16. Being a triple-slot card, this GPU offers 3x HDMI 2.1 and 3x DisplayPort 1.4a, and it draws power from a 2x 8-pin power connector, with a power draw rated at 550 W maximum. Its dimensions are 290 mm x 131 mm x 60 mm, and it features a triple-slot cooling solution [163].

The second implementation is the Gigabyte GeForce RTX™ 3060 GAMING OC 12G (rev. 2.0) [164], launched in January 2021 and based on the GA106 graphic processor (specifically its 300-A1 variant). As per the RTX™ 3070 Master, this GPU fully supports DirectX 12 Ultimate, providing the same types of VR-ready software benefits despite implementing 28 raytracing acceleration cores and offering 3584 shading units. It is coupled with 12 GB of GDDR6 Memory at 192-bit, and it is compatible with PCI-Express 4.0 x16. The card is a dual-slot that powers from a 1x 8-pin power connector, with a power draw rated at 450 W maxim, and it presents 2x HDMI 2.1 and 2x DisplayPort 1.4a. Its dimensions are 282 mm x 117 mm x 41 mm, and it features a triple-slot cooling solution [165].

	GeForce RTX 2070	GeForce RTX™ 3070 Master 8G	GeForce RTX™ 3060 Gaming OC 12G (rev. 2.0)
GPU	TU106-400A-A1	GA104-300-A1	GA106-302-A1
GPU Class	Dual slot	Triple-slot	Triple-slot
Cooling	Dual slot	Triple-slot	Triple-slot
GRAM	8 GB	8 GB	12 GB
GRAM Type	GDDR6	GDDR6	GDDR6
RT Cores	36	46	28
PCI-Express	3.0 x16	4.0 x16	4.0 x16
SU	2304	5888	3584
DirectX	12 Ultimate	12 Ultimate	12 Ultimate
M.L. Tech.	CUDA® cores	CUDA® cores	CUDA® cores
Dimensions mm	L: 229mm W: 113mm H: 35mm	L: 290mm W: 131mm H: 60mm	L: 282mm W: 117mm H: 41mm

Table 4 – Nvidia GPU research implementation against ACCA Software Nvidia GPU recommendation.

4.2.3   SOFTWARE

UsBIM.Reality is the Virtual Reality proprietary software by ACCA Software at the base of this research. It works as a direct add-on implementation on the Common Data Environment platform by the same company, and it is basically a Virtual Reality and Rendering Software. The source code of the computer graphic app is written in C++ language, and it takes full advantage of all the rendering capabilities of the game engine "Unreal Engine 5" [166] developed by Epic Games. Furthermore, it is fully compatible with graphic Application Programming Interface in DirectX11 and DirectX12.

The software can be directly used via the proprietary CDE "usBim.Browser" from any internet browser (provided that internet connectivity is in place). Thanks to the Pixel Streaming technology [167] of Epic Games, the application streams rendered frames directly on the CDE platform and, when activated, into the display of the paired VR goggles using a Web-Socket communication protocol (Figure 10).

The use of the Web-Socket protocol is fundamental for the type of data exchange intended for this software, as through this system, a live connection between client(s) and server can be established, making the exchange of data bidirectional and allowing for the correct functioning of the Pixel Streaming technology. Furthermore, the generation of the VR environment in UsBIM.Reality is based on software libraries that are fully compatible with both Steam and Oculus, making the application by ACCA Software virtually compatible with any VR Headset that uses them.
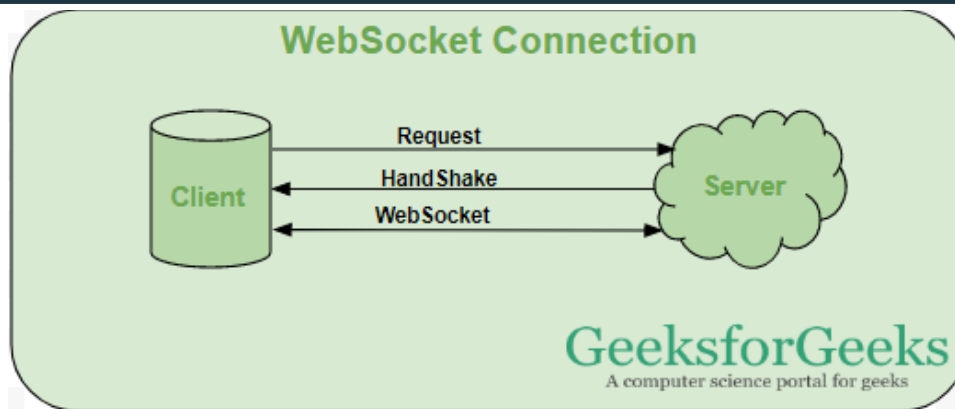
Figure 10 - WebSocket connection representation.

4.2.4   HEAD-MOUNTED DISPLAY

ACCA Software is very generic in terms of head-mounted display recommendations. When it comes to the selection of an appropriate HDM for use with their software, they list all the most used and widely adopted hardware systems currently on the market. Although it demonstrates the adaptability and versatility of their applicative, the lack of specific requirements from ACCA Software unfolds a considerably large choice range because the area of Virtual Reality googles is an industry per se that offers products to amateurs and professionals alike.

Thus, several works, not limited to the AEC industry, have been analyzed to identify the best HMD to fit the research work. The Head Mounted Display selection, in fact, originated from an extensive web search [15], which was topped up through consultations of review articles dedicated to the topic. There are, in fact, important features that have been taken into consideration when selecting Virtual Reality goggles, and, as per recent studies, they can be categorized into three main groups: Image quality, User comfort, and Secondary features [168].

The first group of features fundamentally delves into image resolution and frame rate. Studies confirmed the importance of selecting a VR Head Mounted Display that offers very high resolution, with at least 1440 x 1600 pixels per eye [169] and refresh rates not below 60 frames per second, which is also discussed to be the minimum required to counter the Virtual Reality Sickness effect [170] display typology and Image-to-eye delivery play an important role in the definition of the quality of the image and, consequentially, the quality of the immersive experience. There are currently different ways for VR internal screens (namely, the medium used by the VR headset to project stereoscopic images to the eyes) to transfer images to the brain. The most widely adopted solution is the use of Liquid Crystal Displays (LCDs), which work by dynamically blocking light from passing through to a panel of pixels before entering the eyes through the VR headset lenses. Thus, these types of screens require separated color panels and external (dedicated) light sources to function. LCDs represent the oldest and the most used type of technology for VR screens, making them the most cost-effective. They are also long-lasting and more durable than other systems, typically achieving up to 60,000 screen-on hours without

being plagued by screen burn or dead pixels. However, because of the many parts that compose the display, VR headsets implementing this technology tend to be thicker and heavier than more recent ones. Light-Emitting Diodes or LED lenses stay in a similar predicament to LCDs, but instead of relay on an external lighting source, these displays use their internal light emitter, the diodes themself, or in the case of VR headsets, microLED (μLED). These are the same as LED technology but present much smaller backlighting diodes, achieving a much higher diode density and, consequentially, a crisper image. Thus, LED or microLED back panels can produce stronger levels of luminance, which translates to an overall higher brightness level.

Furthermore, using diodes as lighting for the display also means the size can be slimmed down compared to traditional LCDs, making the VR headsets implementing this technology less bulky and lighter than LCD ones. The setback is that HDM-based Virtual Reality is an enclosed experience, and brightness is less important than contrast and color accuracy and cost-wise, LED displays are considerably more costly. Another form of image-to-brain delivery is based on Organic Light-Emitting Diodes (OLED). The property of these organic LEDs is that they combine the light source, pixel, and light blocking into one. In essence, each pixel (OLED) is a self-sufficient generator of color and illumination. OLED displays, therefore, have incredibly deep black and contrast levels, making the VR experience more real and immersive. OLED can generally guarantee a higher refresh rate capacity than other types of screens. Being among the most recent display innovations, OLED-based VR headsets are the most expensive on the market. However, along with a better Virtual Reality experience delivery, these HMDs present the thinnest and lightest of all the display solutions, and thanks to their low energy consumption, OLED-HMDs are ideal for standalone VR experiences. The only drawback of this technology concerns the lack of deep brightness that can sometimes produce unrealistically saturated colors compared to a more natural image of an LCD and LED [171].

The second feature group, User comfort, concerns the weight and balance of HMD on the user's head, the heat development that the display is subject to, and tracking stability and efficiency. The overall weight of an HMD is affected by the screen typology and the HMD internal battery, especially in the case of goggles that offer standalone VR experiences, which tend to be considerably heavier also due to the integration of both a CPU and a GPU to compute and render the images, in contrast to a tethered system that relays entirely the Graphic Processor Unit of PC. In the case of "all-in-one" type of goggles where all computational efforts are made within the helmet, additional user physical stress is delivered through the considerable heat that the display can reach due to its operation. A comparative study conducted in 2019 has demonstrated that, on average, internal temperature can reach 35º C [172]. Another important characteristic that affects the comfort of HMDs is the user movement tracking capabilities of the Virtual Reality headset. The term refers to the process of determining users' viewpoint position and orientation while immersed in the VR experience, and it is measured by the "Degree of Freedom. The DoF defines the actual number of user movements typology the HMD can recognize and replicate in the virtual environment. VR headsets and input devices are generally either 3DoF or 6DoF [173]. Studies have, in fact, demonstrated that there is a clear correspondence between users' perceived comfort within the immersive experience and the number of DoFs offered by the HMD.

Furthermore, the low latency of users' movement registration and reproduction within the VR environment also plays a key role in comfort, as lagging is recognized among the most impacting factors generating Virtual Reality Sickness [174].

Thirdly, secondary features encompass many aspects of the VR-HMD design, which do not necessarily fall into the above categories but influence the usability of the goggles. Some research-specific relevant secondary items are listed as the presence of an integrated audio system (microphone and speaker) and the system setup complexity, which stands as how easily the HMD can be configured to fit the parameters of the research [175], and the connectivity typology offered by the goggles (preferring wireless connection such as Bluetooth).

Additional research was conducted, based on online comparison websites [176], among the semi-professional VR-HMD on the market by the time of this research, as well as in the literature [177], to finalize the selection of the goggle system to implement on the study. Conclusions were drawn about an overall equivalence between the HTC Vive Pro [178] products and the Oculus (today Meta) Quest products [179]. Thus, given a more accessible price, the need to operate on Windows ambient (instead of macOS, for which VIVE has full compatibility), and considering that the eye-tracking feature is not necessary for this work's aim, the final choice discarded HTC in favor of Meta products.

The head-mounted display selected is a Meta Quest 2 (Figure 11). It is a standalone VR HMD with 1832x1920 pixels resolution per eye on a refresh rate of up to 90Hz, 128GB internal storage, and 6GB of LPDDR4X RAM [180]. It features Fast-Switch LCD Display technology powered by a Snapdragon XR2, a VR-ready CPU from Qualcomm, that implements the integrated Adreno 650 GPU. A single-cell 3640mAh rechargeable lithium-ion battery pack with a 14-watt-hour rating powers the Meta Quest 2 in standalone mode. Alternatively, if tethered via its USB-C cable, the HMD relays on the power input of the connected Desktop while taking advantage of the full graphic power of the dedicated GPU (if any) for the rendering of the Virtual Experience.

Figure 11 - Meta/Oculus Quest 2.

The Meta Quest 2 is a 6DoF Virtual Reality Headset, thanks to the four built-in cameras in the helmet and the two controllers with accelerometer and gyroscope, which compulsory allow for the three types of translation, heaving, surging, and swaying and the three types of rotation, pitching, yawing, and rolling (Figure 12).
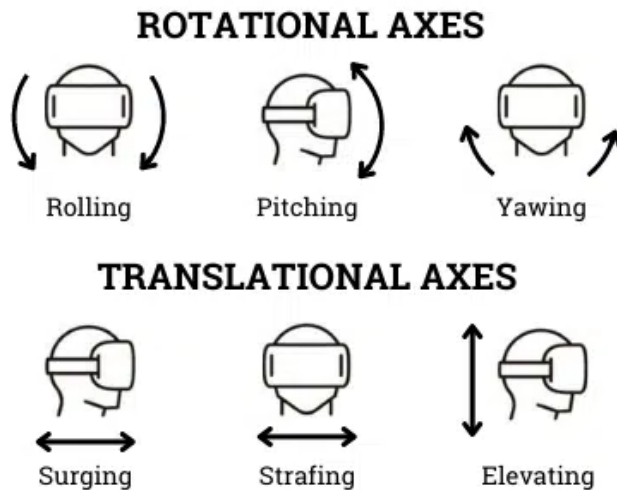

Figure 12 - 6DoF example.

The Meta Quest 2 controllers are a pivotal instrument for the enhancement of the user's Virtual Reality experience and consist of two fairly complicated battery-powered ergonomic handles (left and right hands). Each one is equipped with two triggers, a front one, called index, and a side one, called "grip", and an accelerometer, embedded in the "halo" that crowns the buttons pad. Each controller presents three different knobs located on the pad, two of which are in relief and are identified as "A" and "B" on the right controller and "X" and "Y" in the case of the left one. The third one is the "menu" button, and it is the only key that can activate or recall the software main U.I. of the head mounted display. Finally, a thumb joystick, also positioned on the pad, closes the Oculus/Meta Quest 2 array of toggles (Figure 13).
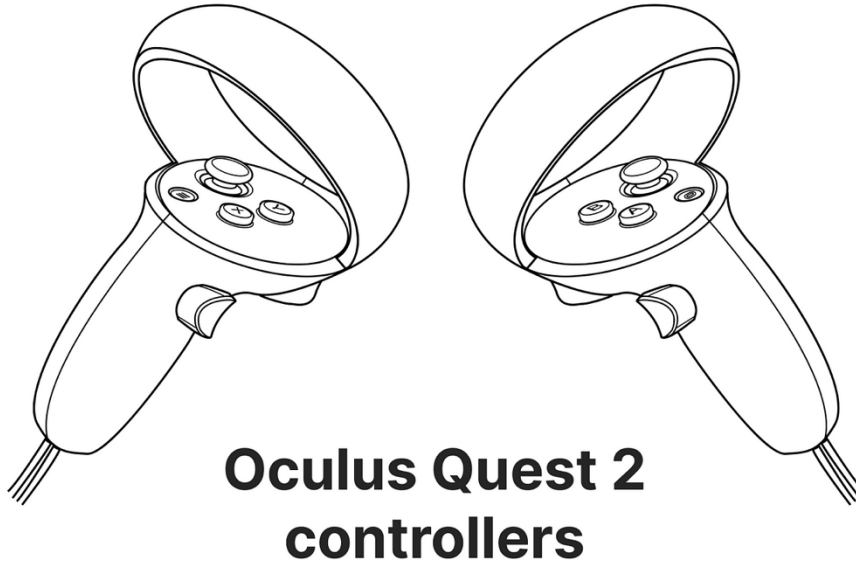
Oculus Quest 2 controllers

Figure 13 - Oculus/Meta Quest 2 toggles.

4.3 CASE STUDY

The case study of this research is represented by the Ritz Carlton Residences Business Bay project (Figure 14) developed by Khamas Group of Investment Co's (L.L.C) and branded by The Ritz Carlton®. It is a twenty-three-stories residential skyscraper located in Dubai Business Bay (Dubai, UAE), and it accounts for a total Ground Floor Area of approximately 25k sqm and a Built-Up Area of 33k sqm, which are distributed on a stacking functional diagram that includes a Ground Floor, a 3 levels parking podium, one level of amenities and common areas and 18 floors of residential apartments.

One of the project's characteristics makes it a valuable proving ground for the testing of the usBIM.Reality software is the absence of a typical floor, which makes the building unique and challenging in terms of design coordination and clash detection. In terms of the vertical stacking diagram, the project presents two very distinct areas. The first portion is the podium, which spans fifteen meters above the ground level and hosts the entrance lobby, three floors of concealed parking, the Ground floor technical areas, and the residence amenities and tenants' services, located on the top floor of the podium. Eighteen residential levels represent the second portion of the stacking diagram. Among the 18 residential levels, in fact, there are 12 different typical floor layouts, which, thanks to the overall section configuration, make the project virtually change at every level. Such diversity is provided by the large number of apartment typologies that present different layout solutions depending on their orientation and position.

Figure 14- R.C. Residences B.B., rendering view.

The design includes 1-bedroom, 2-bedroom, and 3-bedroom apartments as typical typologies, presenting respectively two types of 1-bedroom, five types of 2-bedroom, and four types of 3 bedrooms, for a total of 62 apartments (Figure 15). Additionally, as specifically instructed by the brand, the project accounts for one duplex villa (located on top of the parking podium) and two penthouses distributed according to the shorter building axis on the last floor.

				UNIT MATRIX					
TYPOLOGY	APT. CODE	FLOOR NUMBER	APT. Q.TY	APT. AREA (sq.m)	APT. AREA (sq.ft)	TYPOLOGY Q.TY	%	TYPOLOGY AREA (sq.m)	TYPOLOGY AREA (sq.ft)
VILLA	DUPLEX VILLA	1	1	569,7	6133,01	1	1,5%	569,7	6131,96
STUDIO	ST1	13	1	46.4	499,5	2	2,9%	92,7	995,8
	ST2	13	1	46.1	496,3				
1 BEDROOM	T1A	2-7-9-12-17	5	581,75	6261,96	13	19,1%	1398,73	15055,78
	T1B	2-3-4-8-10-11-15-16	8	816,97	8793,82				
2 BEDROOMS	T2A	4-8-10-14-16	5	770,96	8298,59	26	38,2%	4293,48	46214,69
	T2B	2-3-4-8-10-11-15-16	8	1380,61	14860,80				
	T2C	3-4-8-10-11-15-16	7	1171,95	12614,72				
	T2D	3-5-11-14	4	590,91	6360,54				
	T2E	8-9	2	379,05	4080,04				
3 BEDROOMS	T3A	5-7-9-12-14-17	6	1210,20	13026,51	24	35,3%	4949,64	53277,48
	T3B1	3-4-5-7-10-11-12-15-16	9	1812,58	19510,44				
	T3B2	2-14-17	3	593,99	6393,66				
	T3C	5-7-9-12-14-17	6	1332,87	14346,87				
PENTHOUSE	PENT01	18	1	333,49	3589,63	2	2,9%	706,52	7604,88
	PENT02	18	1	373,03	4015,25				
TOTAL			68	12.010,07	129.281,6	68	100,0%	12.010,07	129.281,6

Figure 15 - R.C. Residence BB apartments schedule.

The residential floors shall take into consideration also a different setback from the plot limit than the lower levels, namely the Ground Floor (Figure 16) and Amenities Floor, to ensure the respect of Dubai Municipality restrictions in terms of view sight angle and windows-to-windows minimum distances. Furthermore, the building core solution represents an important challenge for the overall architectural design since the project develops around a structure that was pre-designed (basically, landed from another development) and not studied from scratches from the early stages of the project.
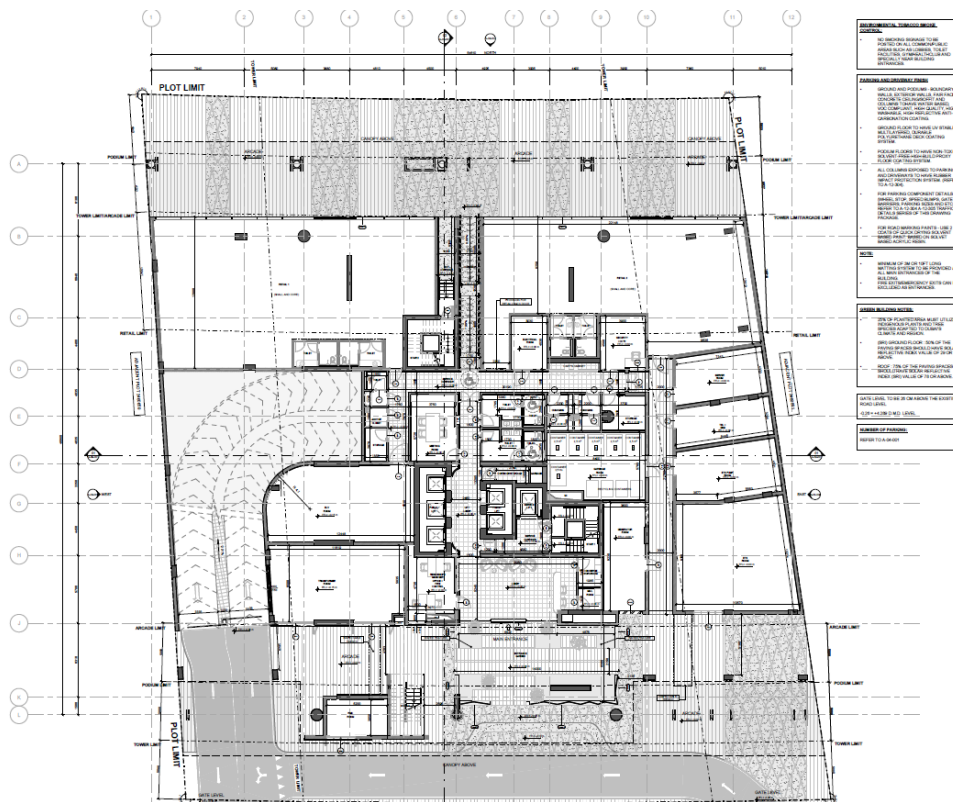

Figure 16 - R.C. Residence BB Ground Floor.

Further into the design development, the structural solution was re-visited in terms of position and number of columns to allow for a cleaner façade design. Thus, the slab solution was reassessed, optioning for post-tension technology to guarantee feasibility despite the long spans and the limited number of vertical supports. Aside from the architectural layout and structural challenges, the project presents other aspects that require attentive coordination. The residential levels' floor-to-floor height of just 4.15m and the PT slab solution implemented in the project calls for highly precise MEP coordination. On top of that, with the extremely diverse floor plans, particular efforts must be made to guarantee clash avoidance among the MEP discipline to ensure efficiency and functionality. The major issue in this sense is represented by the constant floor-to-floor piping deviations due to the ever-changing bathrooms' location (and related shafts) and the need to strictly adhere to the Ritz Carlton standards, which forbid any piping distribution in dry areas within the apartment spaces.

Additionally, the project presents a double layer façade (Figure 17) composed of a fully glazed internal one in direct contact with the interior of the apartment, and a metal louvered external system that provides shade to the terraces and the inner layer. The slab edge of the terraces tends to follow the lining of the inner curtain wall (namely the apartment interior perimeter), but given the variety of apartment typologies and their almost random distribution, it is virtually impossible for the louvered façade to align and match the position from one floor to the other: ergo, the call for extra care in design coordination.
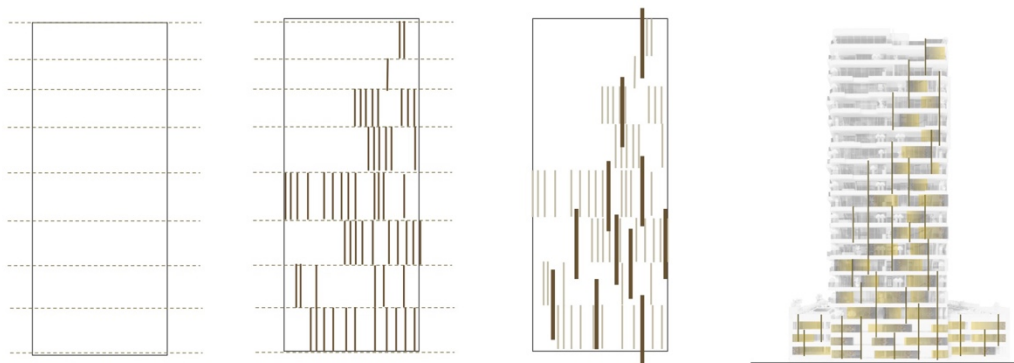

Figure 17 - R.C. Residence BB facade scheme.

Finally, several international stakeholders actively participate in the design, intervening in the project from three different continents, increasing the need for efficient communication and information sharing among parties. All the above-mentioned design and planning situations make the digital twin of the project a good test subject for the proprietary VR system in a CDE environment of ACCA Software, testing its capabilities and functionality for design coordination and clash detection.

By the time this research work is completed, the case study will present the podium structures implemented on-site and the post-tension slabs for the first seven residential floors in delivery.

4.4   METHOD

As demonstrated by previous works, Virtual Reality has become mature enough to be effectively implemented in the AEC industry as an integral part of the workflows that characterize the many phases of a project life cycle. The extensive review conducted has highlighted that the Design Stage is one of the project phases where this technology can provide major contributions, specifically in the function of supporting design and stakeholder coordination, facilitating the information flow, and enhancing its quality. In short, VR proves to be highly effective as a Design management tool.

ACCA Software has always been at the front line of the AEC industry innovation segment, and it is now fully implementing eXtended Reality technologies, in particular Virtual Reality, within its product offers. As previously discussed, this work aims to support the Italian software house in developing the VR application (usBIM.Reality) within its proprietary Common Data Environment (usBIM.browser), approaching the improvement of the software from the final user standpoint. Thus, the research efforts have been reasonably practical and followed an empirical and applicative approach. Although described and explained as a sequence, the research efforts were not all performed linearly in a "waterfall" fashion, with one item consequentially following the next, but instead, the data collection and related analysis followed a more "agile" approach, configuring as an iteration of steps.

The first one consisted of fine-tuning the hardware setup needed to compute and generate the Virtual Reality experience properly. As explained in previous paragraphs, the hardware requirements to efficiently run the software are not ordinary due to the considerable computing power needed to withstand the graphic stress produced by VR on the machine. Ergo, despite the hardware adherence to the specifications received from ACCA Software, the first step took considerable time and substantial refining, culminating with the assembly of a VR-dedicated desktop computer and the achievement of the necessary milestone to open up all other treads.

The second step consisted of performing evaluation tasks on the BIM-twin of the case study, aiming at testing the VR software and identifying weaknesses and potential improvements. The direct experience and experimentation consisted of 4 sessions (referred to in the rest of the document as iterations), roughly thirty minutes each, leading to the identification of 12 issues (in the Beta version of the software)
The third step consisted of grouping the perceived necessary interventions by typology, classifying the required improvements into four categories:

- Program Logic: It refers to problems or refinements related to how the software operates or responds to specific user actions/inputs.

- **User Interface (U.I):** It refers to problems or refinements strictly related to how users can input information or perform actions within the Virtual Reality environment.
- **Graphic:** It refers to problems or refinements that concern the graphics of the Virtual Reality environment and its impact on the user experience.
- **Modeling:** It refers to problems or refinements specifically related to the actions that users can perform within the Virtual environment and on the model.

A priority scale was introduced to describe the issue's impact on the overall workflow as perceived from the user standpoint, to support the classification of the issues, and to aid the ACCA Software R&D team in their development work. The scale of priority that floats from 1 to 5 (where the first indicates minor urgency and the latest describes the highest one) was used to signal the developers about which problem to intervene on first. To better understand the potential and limitations of the software, the four iterations revolved around some of the most common aspects of design management. In short, the research had user(s) performing a series of tasks related to design review, clash detection, and information recollection on the interactive BIM-twin of the project in an immersive and collaborative multi-user Virtual Reality common data environment.

The fourth and final step revolved around compiling the recommendation matrix, ordering the documented issues based on the priority scale, and providing validating walkthrough videos in addition to a written description of the problem along with a suggestion or recommendation on potential fixing. After the direct experimentation that lasted four months, a recommendation matrix was constructed and issued as the final set of feedback to ACCA Software, which used the matrix to integrate part of the suggestions within its final product, which was launched on the market in the first quarter of 2023. The matrix articulates around six elements (Table 5).

IUAV	ACCA usBIM.Reality ASSESSMENT MATRIX				
Item number	Typology of comment	Comment	Comment's Priority	Reference	Notes
# Number of the items in sequential order	Definition of which group the comment relates to	Detailed description of the item to clarify and explain the concern	Priority of implementation based on the perceived relevance from a user perspective	External referenced links to either a video or a picture taken directly in VR to give context to the issue description	Provided documentation, either descriptive or visual, on how the issue could potentially be solved.

Table 5 – Recommendations Matrix breakdown.

The first column identifies the issue number, providing the sequence of the identified problems. The second column defines the "Typology of comment", listing the issue within one of the five

aforementioned group categories. The third column, "Comment", aims to describe the issue in terms of how the problem affects the user experience, while the fourth and fifth columns, "Comment's Priority" and "Reference" provide, respectively, the gravity of the found issue within the metric described before, and a graphic or video reference to contextualize the issue and better grasp the referred gravity index. Finally, the sixth column, "Notes", details potential solutions or suggestions on how to intervene in the problem to either fix the issue or lower its gravity index. It is worth noting that the final Matrix organizes the items per groups, instead of ordering them by level of priority or manifestation. The type of clustering selected intends to facilitate the issues typology screening by ACCAsoftare R&D specialists.

As previously mentioned, usBIM.Reality was in the Beta stage by the time this research was conducted. Thus, not all the tools available in the U.I. menu were fully developed or usable through the experience in VR. Due to this "implementation gap" some actions on the model were not possible but were not listed nor accounted for as issues in the recommendation matrix that focused instead on perfecting the available tools. It is also important to point out that the software tested underwent two updates during the time frame the iterations took place, and although most of the improvements concerned the application stability and the fixing of code bugs, they also happened to improve some of the issues found. Ergo, the problem listed in the matrix addresses the "latest" version of the issues, and the related suggestion indicates how to improve it further.

5 RESEARCH DESCRIPTION

5.1   HARDWARE ASSEMBLY AND PREPARATION (FIRST STEP)

As previously explained, the first input to the research concerned the hardware assembly for the software operation based on the characteristics specified by ACCA Software (described in the paragraphs above). This process encountered several setbacks due to specific hardware-software incompatibility that caused a delay in the beginning of the testing. Drawbacks were expected, given the "in progress" nature of the Beta stage, and they led to the identification of some criticalities later addressed to ACCA Software. One issue in particular, the acceleration of the graphic power via eGPU, created a stall in the research, and the R&D team could not correct the issue within the time frame of the data collection due to coding constraints and the company priority schedule.

As implementing an external Graphic Processor Unit was incompatible with the current software development stage, the only workaround possible was to set up a new hardware solution, still responding to the specification but presenting a dedicated GPU.

5.1.1   FIRST HARDWARE SETUP

The first hardware setup for this research is based on a MacBook Pro, 13" 2020 4 Thunderbolt3 ports (Figure 18), with Chipset Intel I-7 Quad Core and 16GB RAM DDR4 with integrated GPU Intel Iris Plus [181], which corresponds to the CPU selection described in the previous paragraphs.

The decision to use an Apple computer presents the advantage of having a very durable and stable laptop whose build and performance are well-documented and easily repeatable [182]. It also represents a considerable obstacle to implementing the BIM software since UsBIM.Reality runs only on the Windows system. A Bootcamp partition was initiated on the MacBook Pro, allowing Windows 10 Pro to be installed, overcoming the BIM software compatibility issue. The major impediment to the experimentation of the usBIM.Reality concerned the software's requirement for a high-performance GPU to operate, as graphic acceleration is needed to run the software properly. The technical side presented quite a challenge to the research because Apple laptops do not present the option of retrofitting or expanding the graphic card power.

To solve the problem, extensive research was conducted on the possibility of implementing an external GPU (eGPU) [183] to the MacBook Pro within the Bootcamp Windows partition. The most significant information basin was found in a dedicated forum webpage [184], which provides extensive case examples and detailed explanations about their installations, pros, and cons. Any user can thus search the vast repository via a set of seven different types of filters, obtaining a perfect or quasi-perfect match with their specific situation. The GPU selected for the implementation in the case study is an Aorus Nvidia GeForce RTX™ 3070 Master 8G with 8GB RAM DDR6 at 256-bit that supports OpenGL 4.6 and has a digital max resolution of 7680x4320 pixels.

Figure 18 - MacBook Pro, 13" 2020 4 Thunderbolt3 ports.

The enclosure case (Figure 19) for the support of the GPU is a Razor Core X Chroma [185] with internal ATX 700w capable of directly power-feeding the laptop via a USB-C connection (Figure 19). The selection of this model originated from its proven compatibility with both Windows and macOS ambient.

Figure 19 - Razer Core X Chroma & Nvidia RTX™ 3070.

Although the eGPU setup was perfectly aligned with the laptop configuration, the first installation of the external device was unsuccessful due to the Bootcamp Windows-built version operating on the machine. The process kept returning Windows error code "12", the impossibility of the device finding enough resources to operate, signaling a system conflict. The issue was solved by formatting the Windows partition and installing a specific Bootcamp Windows built (version 1903.30). After installing the specific Nvidia proprietary drivers, the GeForce RTX™ 3070 read correctly and started operating as expected. Unfortunately, the now fully operational hardware setup could not load the Virtual Reality application correctly as an error ascribed to using an eGPU kept arising (Figure 20).
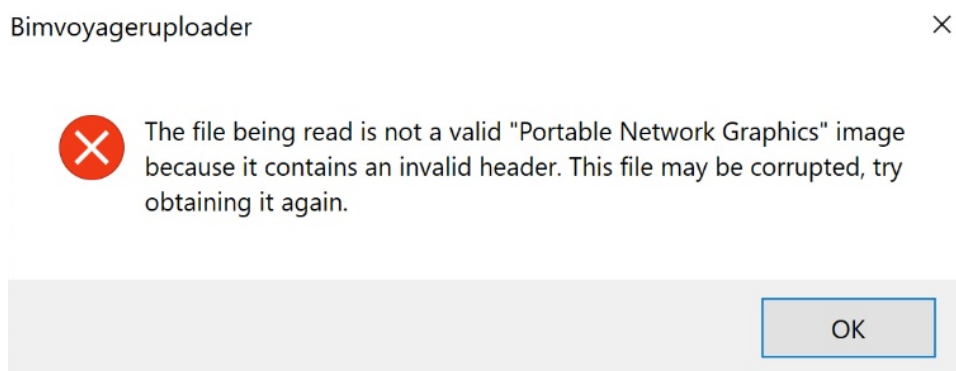

Figure 20 - Windows error on eGPU.

5.1.2   SECOND HARDWARE SETUP

The chosen base of the second hardware setup is an assembled Intel® NUC 11 Extreme Kit - NUC11BTMi9 [186] (Figure 21), which presents an Intel I-9 Chipset with 8 Cores and a predisposition for RAM DDR4 up to 64 GB. This specific machine was selected among other possible bases as per the information received from the developers of ACCA Software, who analyzed the errors' code returned by the software implementation on the first hardware setup and formulated a recommendation list, suggesting a specific Central Processing Unit (CPU) system and manufactures [187].

The NUC 11 is a high-performance semi-assembled mini-PC with a clock speed of 3.3 GHz (4.9 GHz Turbo), 8 cores, 16 threads, and 24 MB of Cache, which represents a fair benchmark of VR-ready computers available on the market and satisfies the specification suggested by ACCA Software developers. The machine presents an integrated Intel® UHD Graphics with a Clock of 350 MHz – 1.45 GHz, unsuitable for the high-demanding graphic performances that Virtual Reality applications require. Thus, a dedicated GPU was purchased separately and installed on the machine. It is important to point out that the Aorus Nvidia GeForce RTX™ 3070 used in the first hardware setup could not be implemented in this case due to the "limited" available space of the Computer Case. The Intel® NUC 11 Extreme Kit can integrate graphic cards up to 30 cm in length,13 cm in width, and 4cm in height, which the Aorus Nvidia GeForce RTX™ 3070 Master 8G does not respect, being 29 cm x 13 cm x 6 cm.

Figure 21 - Intel® NUC 11 Extreme Kit - NUC11BTMi9.

The new GPU selected for the implementation on the NUC 11 is the Gigabyte GeForce RTX™ 3060 GAMING OC 12G (rev. 2.0) with 12GB RAM DDR6 at 192-bit that supports OpenGL 4.6 and has a digital max resolution of 7680x4320 pixels [164]. The benchmark comparison provided by PassMark Software between the two GPUs selected informs that the GeForce RTX™ 3070 performs overall 23,7% better than GeForce RTX™ 3060, with a G3D score of 22495 for the 3070 against 17171 for the 3060. Regarding specification, the two graphic cards show minor differences, particularly in CUDA cores, memory size, bandwidth, and clock speed [188]. For the research purpose, the most significant difference between the two graphic cards consists in their Frame Per Second (FPS) performance, in which the Aorus Nvidia GeForce RTX™ 3070 achieves roughly 30% higher results than the Gigabyte GeForce RTX™ 3060 (Figure 22).

Figure 22 - Gigabyte GeForce RTX™ 3060.

5.2   ISSUES IDENTIFICATION AND DATA COLLECTION (SECOND STEP)

The actual data collection process could only begin after the second hardware setup was successfully assembled and all the necessary drivers were installed on the operating system. To properly operate the bridging between the Desktop computer and the HMD, the Oculus application runs in the background on the PC throughout the entire duration of each experience per session.

Once the web application usBIM.Browser is open, and the portal login is authenticated, the user is given access to the folders in which the BIM information of the case study is stored. After the federation of the IFC files is completed, the user can engage the game engine and launch the real-time rendering visualization mode (Figure 23). After the mode is activated, the application prompts the user to start the VR experience by selecting "usBIM.Reality" from the menu.
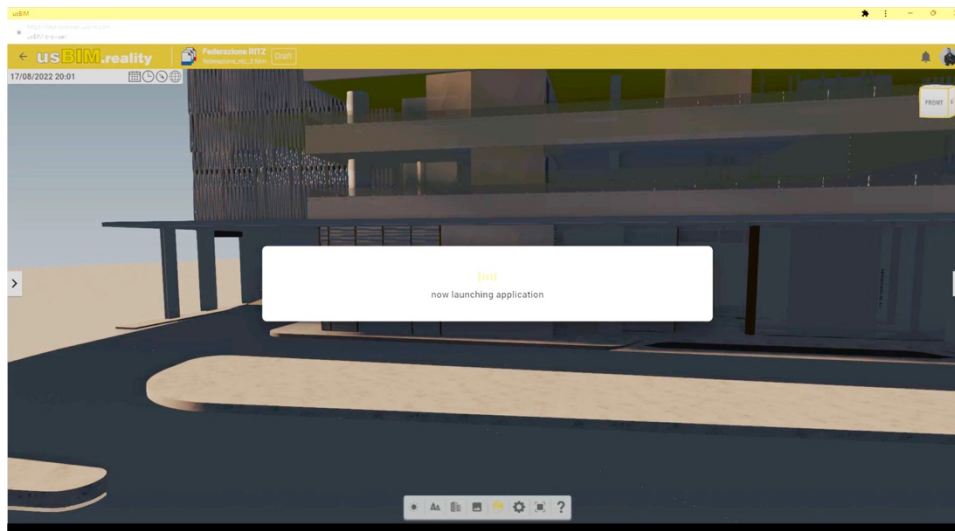

Figure 23 - usBIM.Browser real-time rendering launch.

Although ACCA Software does not integrate usBIM.Reality as a stand-alone application directly executable from Head Mounted Display, the Virtual Reality launch routine described above can be initiated while wearing the Oculus, thanks to the bridge offered by the Oculus software. It is, in fact, possible to "mirror" the screen(s) of the Desktop while in Virtual Reality and fully operate on them, making the process of accessing usBIM.Reality more seamless by cutting the "HMD off – HMD on" lag.

Once the BIM model is fully loaded, the Virtual Reality experience begins (Figure 24), and the user is presented with an immersive 1:1 visualization of the project that can be explored and interacted with via the use of the HMD, two controllers and the set of tools made available by the software.

Although not fully developed (as it was previously explained, usBIM.reality was in a Beta state during the research), the software presents numerous tools that grant users several VR-related abilities supporting the experience and model exploration.
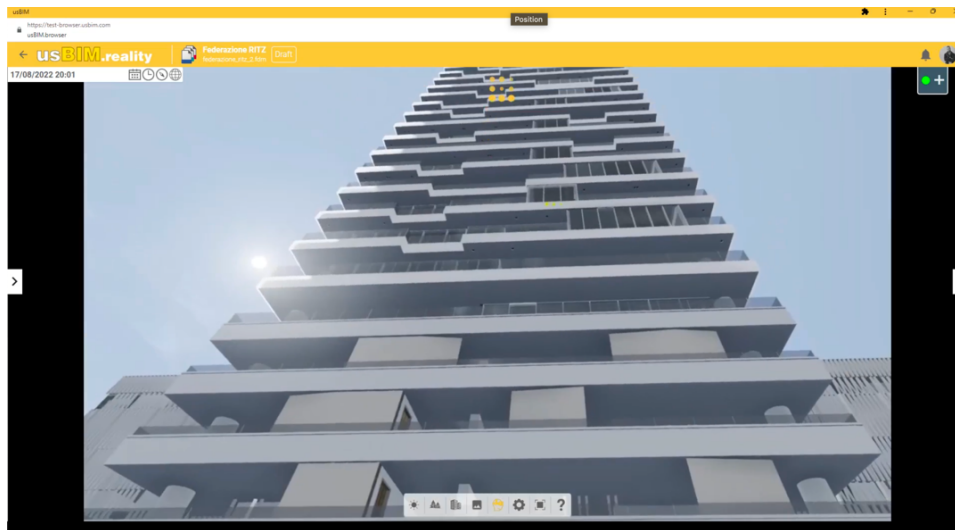

Figure 24 - Immersive VR project loaded.

Each tool can be accessed only through the Main Menu, in turn, activated by pressing either the "B" or the "Y" button of the Meta Quest 2 controllers, that spawn the Main menu wheel (Figure 25). Using the controller cursor, the user can navigate and select any of the circular icons on the wheel, eventually entering the related sub-menu or activating separate functions.
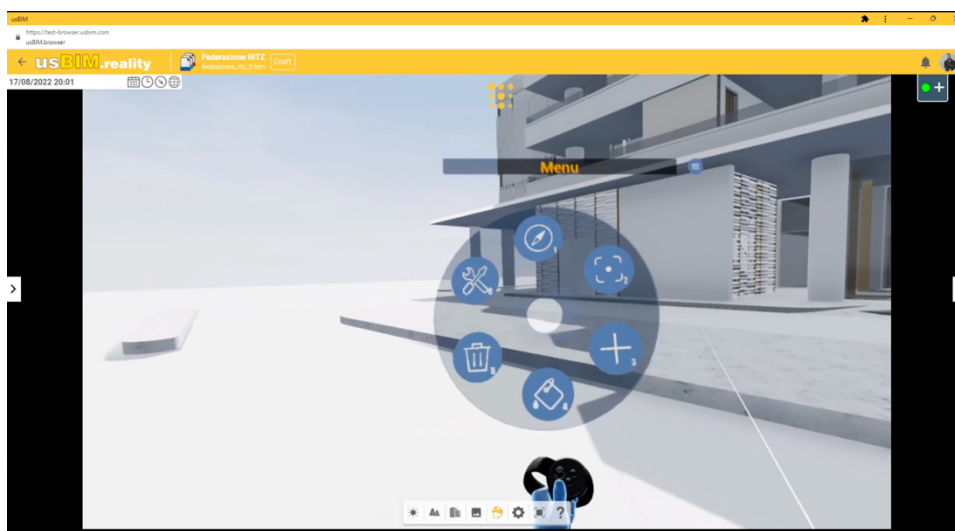

Figure 25 - usBIM.Reality Main menu wheel.

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The main menu of usBIM.Reality presents substantially two sub-menus, the Tools menu and the Edit-Object menu, while the functionalities directly operable are the Navigation function, the Insert object function, the Change material function, and the Delete object function.

Once triggered, the first sub-menu spawns a window that makes new functionalities available to the user, namely the Change position function, the Weather function, and the Measurer function (Figure 26). Triggering the first one recalls a list of pre-saved locations on the model (if any), which the user should be able to access and instantly transfer the avatar to. The second function allows the user to re-configure and alter the weather conditions of the VR environment and assess the related impact on the project. The third voice of the sub-menu activates a laser tape that allows the user to take distance measurements on the model.

Figure 26 - usBIM.Reality Tools menu – Measurer.

The second sub-menu recalls a new wheel that spawns two additional functionalities, allowing the user to either Select an object or Move it. Triggering the first one leads to a window that provides access to all the Edit object functionalities, some of which could have already been activated from parents Menus (such as Change material and Delete or Move object). The main difference between this instance and the other object-interaction functionalities lies in the possibility of visually highlighting the selected item and then choosing the action to be performed on it instead of immediately triggering the operation. Finally, the extra functionality offered via the Edit object menu is Web Browser that allows the user to connect to ACCA Software repository while still in VR and download ready-to-use BIM objects directly onto the model (Figure 27).

The other Main menu functions are quite self-explanatory and can be triggered to operate on the model directly without first selecting which object to prefer the action.
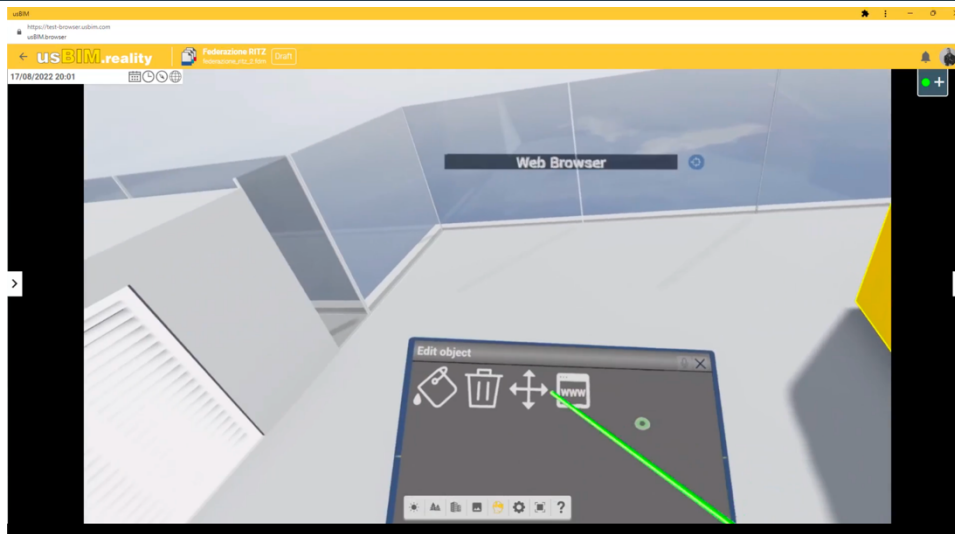
Figure 27 - Edit Object secondary menu - Web Browser.

5.2.1 FIRST ITERATIONS

The first actual software test was conducted in August 2022 and provided the ground for the subsequent iterations. The experience was conducted on the federated model of the case study, which incorporates some of the BIM information expected from the final project virtual twin, as the stage of the design was not yet mature by that time.

During this first experience, the data collected referred specifically to the perceived usability and ease of adaptation to the software. In this case, the test aimed at understanding how quickly the user could become familiar with the software logic and main functionalities to freely roam the Virtual Reality environment with sufficient spatial awareness [189]. By the time the test was conducted, the user had some familiarity with Virtual Reality and the walkthroughs in a virtual environment, ergo cannot be considered a first timer. The experimentation lasted roughly twenty-five minutes, including a ten-minute window of acquittance with the software, during which the user freely roomed the virtual environment, assessing the rendering quality of the BIM model and the maneuverability of the avatar.

Although meant to be "preparatory" in nature, the experience brought to light some software flaws that were considered relevant enough to be listed in the recommendation matrix. The problems identified concerned specifically the usability and operability of the software in terms of movement constraints and the degree of customization that the user is allowed to implement on the jump function (Matrix 4, 5, 9). The issues limited the maneuverability of the user avatar within the Virtual Environment and, consequentially, the overall user experience.

5.2.2 SECOND ITERATIONS

The second Iteration took place relatively close to the first test and lasted approximately as long. This time, the experiment was set to simulate a single-user design review session, during which the model

was explored aiming at finding design inconsistencies and potential improvements to the look of the building.

UsBIM.Reality offers a large set of tools to the users (i.e., tape measuring), which can be recalled directly from each one of the hand controllers via the dedicated button. Pressing the "B" key on the joystick, the main menu pops up on top of the controller, and the tools menu can be recalled using the pointer of the other handle. The user then activates the command using the front trigger of the pointer controller. It is important to point out that the selected command activates on the controller that the user opened the tools menu with, and it remains active on that specific joystick until a new menu is recalled. Having two ambivalent controllers functioning throughout the experience, the user should carefully discern which controller to use for tool activation to avoid discomfort or difficulties in operability.

Interesting aspects of design review tools offered by the software regard the possibility of directly modifying design elements while virtually exploring the model. The "edit object" menu, recalled from the main menu as per the sequence previously described, gives access to a set of tools that allow for intervention on the model, modifying and changing instances of design.

The experience conducted at this stage identified important gaps in the actions allowed for by the tools selected, especially in terms of precision and usability (Matrix 1/10/11), that can compromise the design review session if not corrected.

5.2.3   THIRD ITERATION

The third testing session took place approximately a month after the second session and required the installation of patches and updates of the software due to extensive development work conducted by ACCA Software R&D department. Once downloaded from the server and installed on the computer, the software behaved as a fresh installation. Ergo, browser logging was requested again to access the federation model and resume the experimentation.

The testing scenario, in this case, picked up from the second Iteration and aimed first of all at verifying the persistence of the previously encountered issues. Provided the installed update and the cleared bug that the new software version offered, chances allowed for a potential fixing of the problems previously described, although the recommendation matrix was not yet in place. It was noted that the previously encountered problems were still unresolved, and it was possible to identify one additional graphic issue previously skipped (Matrix 12) and one possible improvement to the way users are allowed to navigate on and around the model (Matrix 6).

The test within the Virtual environment was again conducted as a single-user session, mixing design review with BIM information retrieval and management. The coordination of information is, in fact, one of the most important and relevant aspects of design management and some of the available functions of usBIM.Reality tools menu are intended for recalling data stored in the BIM model under review.

In principle, the session aimed to test the data retrieval functionality and identify potential improvements. The operation is again conducted via the tools' menu, selecting from the main menu, which should allow the user to select the model BIM item and lead to a pop-up dedicated window from

which to retrieve, read, and add data. The dedicated session proved completely unsuccessful in terms of information management tool testing, as the software crashed multiple times, making the session impossible to continue and forcing the user to reboot the entire VR experience from the CDE browser application.

Although the test represented a failure concerning the goal set for the experiment, the Iteration was successful in highlighting a major issue that needed the attention of software developers in the R&D department. Provided the extent of the problem and given the importance of the tool that was failing, the specifics of this issue (Matrix 3) were transferred directly to the of ACCA Software without waiting for the completion of the recommendation matrix.

5.2.4   FOURTH ITERATION

The last testing session took place in November 2022 and was the longest and most intensive of the four iterations, taking up almost one hour and simulating a multi-user project presentation and clash detection meeting. It is relevant to highlight that this session was also performed on an updated version of the usBIM. Reality Beta, which was released by the R&D department of ACCA Software with the aim of testing features concerning users' co-presence on the BIM model.

During this Iteration, in fact, four participants attended the Common Data Environment project assessment from two continents and three locations using different visualization mediums. Two users were connected to the CDE via Virtual Reality HMD, while the other two participants used a regular internet browser on a flat desktop screen. Communication and interaction on the BIM model were simultaneous and in real-time (provided the acceptance of some inevitable connection lag due to the intercontinental data stream). The test conducted aimed at highlighting improvements implemented to software, specifically related to the BIM data retrieval from objects and their fruition by users, which worked seamlessly after the update. The session proved successful in demonstrating the implementation of the information management functionality, now fully accessible from the tool's menu, and it also helped in discovering some overlooked issues related to the CDE co-presence. Although the experience was initiated simultaneously, users with less performing hardware could access the BIM-twin with a certain delay compared to the VR testers, creating some communication lag and consequent misplaced sense of presence (Matrix 8/7). Furthermore, some challenges were highlighted concerning keeping up with other users' movements and actions (Matrix 2) during the project presentations and clash detection, which called for solutions in the future releases of the software.

5.3   FOUND ISSUES DEFINITION AND GROUPING (THIRD STEP)

Throughout the four months of experimentation and texting process the found issues have been analyzed for similarities and least common denominator among them. The intention was to group the problems to facilitate their classification and their presentation to ACCA Software, allowing the R&D

department to understand the issue easily and clearly. The second aim of the group classification was also to present the problems in an organized fashion that might allow ACCA Software specialists to immediately grasp the urgency and typology of the issues found, placing the R&D in the condition to decide whether to intervene on one of them, multiple or any.

The group classification follows the one highlighted in the previous chapter and will be presented based on the number of issues collected for each category.

5.3.1   GROUP 1: PROGRAM LOGIC ISSUES

This group collects software issues and suggestions that relate to how the software operates and responds to specific user actions/inputs. The category also presents items that identify flaws in the form of inconsistencies or software bugs, preventing the smooth or correct operation of the application itself. Overall, throughout the four iterations of this research, a total of six instances have been included in this group.

The **first** issue collected in this group was highlighted during the second Iteration and concerns the measurement tool, located in the tools' menu. The problem described in the matrix shows the impossibility of determining the orientation, perpendicularity, or parallelism of a taken measurement, in respect of the surfaces the measurement refers to. Whenever a measurement is approached, the software provides the user with a visual representation of the connection between "Point A" and "Point B" via a green line that persists in the Virtual environment until a new measurement is taken or the measuring tool is removed from either one of the controllers. Unfortunately, the software does not provide any information concerning the quality of that measurement (Figure 28).
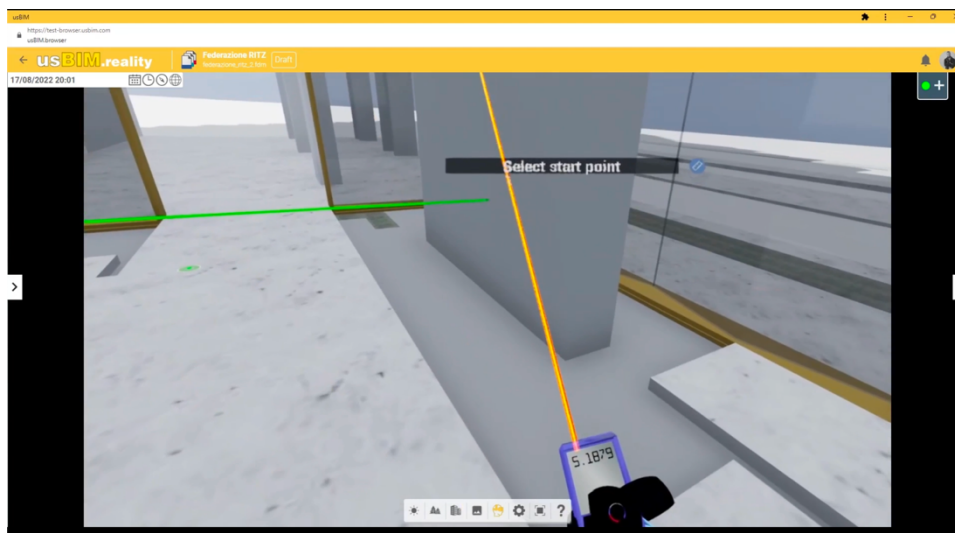

Figure 28 - Measuring tool lack of geometrical cues.

There is no indication, neither visual nor descriptive, about the relation between the two points that identify the measurements. The software provides neither information about the angle in reference to the surfaces that the points are located on nor an indication of the distance of the measurement points from the horizontal plane of the Virtual environment, making it virtually impossible for the user to utilize the information or relay on it properly.

The **second** issue found in this category is highlighted during the fourth Iteration and refers to the impossibility of creating "snapshots" of the current user's Point of View (PoV) referencing it with an XYZ position within the Virtual environment. The software, in fact, does not allow for "geolocating" the user position in respect of the BIM model, nor does it provide tools for creating referenced screenshots of the user's view. The lack of such functions prevents users from "freezing" their location on the model at a given time, making it impossible for them to revisit or re-experience the view/position at a later stage. The issue makes performing design coordination and clash detection more challenging, particularly in the case of large and complex projects. It also represents an obstacle to the smoothness of interaction required during a client Virtual presentation.

The **third** issue in this group is a software bug, discovered during the third Iteration and listed within this category because the problem concerns the functioning of the software itself. Once in the Virtual environment, the user should be able to access online BIM repositories via a dedicated tool, pick the additional information desired, and link it to the model, allowing other stakeholders to access it and retrieve it from the BIM twin of the project. The function aims to allow users to upload onto the model and into the VR experience useful or important information that might be employed during design reviews, client presentations, or even clash detections. Unfortunately, by the time the third Iteration was conducted, the described tool was only partially implemented in the software code. Thus, triggering the command caused usBIM.Reality to freeze and consequentially to crash, forcing the user to restart the experience.

The **fourth** and **fifth** issues of the group concern the movements of the user's avatar within the Virtual Environment. A study conducted by the King's College London in 2019 identifies the "behavior of avatars" and the "interactivity with the environment" among the eight factors influencing the user's sense of presence and immersion in the Virtual world [190], and already at the first testing session it was possible to highlight some fundamental flaws in the maneuverability of the avatar, limiting its interaction with the environment and affecting the user's overall experience. The software, in fact, does not allow for "back walking "and "POV turning" via the joysticks. It is impossible to pivot the point of view of the avatar or have it walk backward simply operating the movement using the controllers. Instead, the user has to act in the real world and rely on the HMD accelerometer to translate it into an Avatar's movement. Therefore, any model exploration requires a considerably large free space in the real world to perform movements, which are subsequentially translated into the Virtual environment. Such issues de-facto

cancel the option of roaming the model while being sited, greatly limiting the accessibility of the software and prejudicing the user's sense of presence and sense of immersion.

The **sixth** item listed in this group regards another type of avatar's movement, specifically its positioning or re-positioning within the model and its surroundings. This issue, experienced during the second testing session, highlights the impossibility of relocating the avatar in any part of the Virtual Environment, at any given time, at will. The jump tool does not respond nor resolve this specific problem, since it is designed to replace and speed up the walking action. The item identified, instead, concerns the possibility of selecting a specific point of the model or the virtual environment where the user's avatar can materialize, an action called "spawning" (and "re-spawning"). Although the software presents the possibility of geolocating the model, it does not present any GPS feature that allows for the univocal identification of the avatar's position on the model. Thus, it is impossible to "pick up" the avatar from a given point and "drop" it on the new desired one (Figure 29).

The function is particularly useful in the case of large or tall projects, where opposite location points on the model can be quite far from each other, largely limiting the related reliability and usability of the jump tool. The spawning function can also increase the practicality of the avatar movements within the Virtual Environment, increasing the model exploration efficiency while speeding up relocation. Most of all, the lack of such a tool prevents the users from selecting the point of spawning when first entering the Virtual experience or potentially relocating next to another user while visiting the model in co-presence.
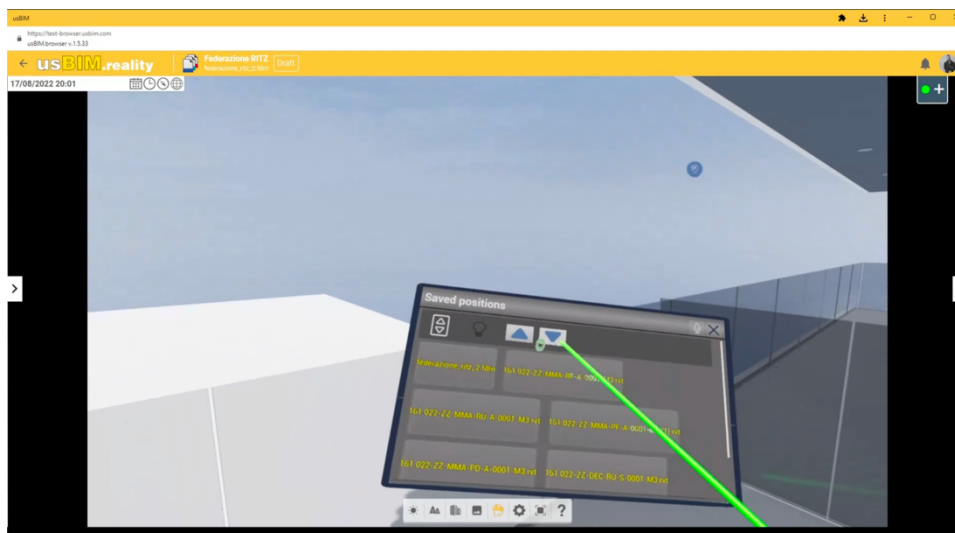

Figure 29 – Pre-saved model locations.

The **seventh** and last item of the group was identified during the fourth Iteration and referred specifically to adjustments concerning how the software initiates the virtual experience. As previously

explained, the hardware setup plays a very important role in the generation and computing of the Virtuality, and the quality of the experience is largely dependent on the performance capability of the machine itself (Figure 30). When performing collaborative tasks, users are spawned in the VR environment as soon as the experience is initiated instead of allowing for the time that the hardware needs to generate the environment (and the model itself) in which the actions will take place. As a result, when multiple users access the model via different hardware systems, they might experience a scattered environment because the software lets them in the virtual environment before completing the rendering and generation of all the features. Such an instance can lead to user disorientation and consequent low sense of immersion, which can ultimately cause discomfort and potential loss of balance in the real world.
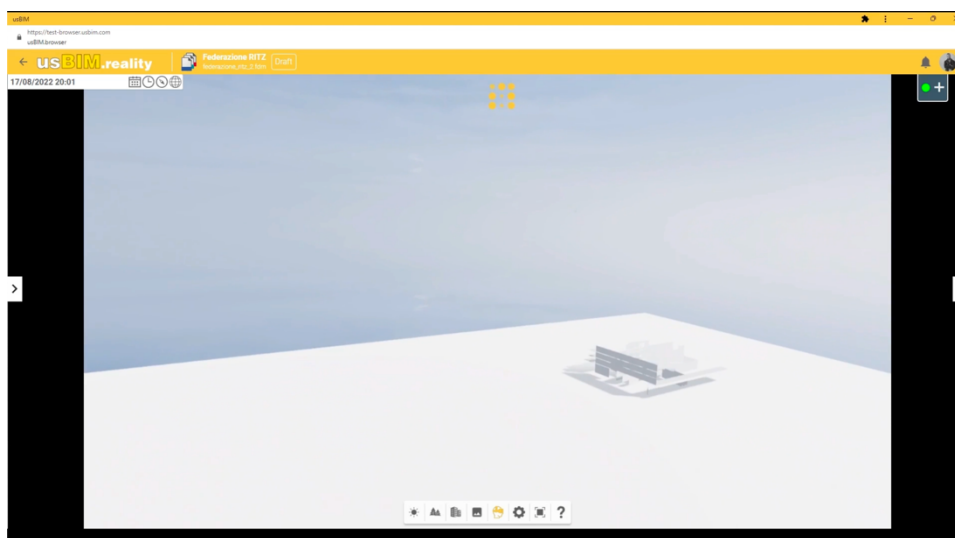

Figure 30 – Generation of the model in the VR Environment.

5.3.2   GROUP 2: USER INTERFACE (U.I.) ISSUES

The second category collects all the issues and recommendations that are somehow related to the User Interface of the software, including problems or refinements associated with the way users can input information or perform actions within the Virtual Reality environment. The four iterations conducted led to identify two issues that belong to this group.

The **first** item of this category was identified during the first sessions and concerns the movements of the users within the Virtual environment. Specifically, the jump tool is a "shortcut" that grants the ability to jump from Point A to Point B instantly as if the avatar was, in fact, teleporting. The command is selected from the main menu and can be activated on either of the two controllers. Once active, the user can point the controller in any direction, and the software will return an arc, providing a visual "aid" to understand where the avatar will be exactly relocated. The user can then perform the jump by

pressing and releasing the front trigger of the controller on which the command is active. The length of jump that the software allows is fixed, and the movement is also subject to the concept of gravity (Figure 31). Ergo, the user can extend or reduce the jump size by a mix of correctly positioning the controller and properly locating the avatar (i.e., if the avatar is on the roof of a skyscraper, it is possible to teleport to the ground floor, but the way around is not allowed). The software does not offer an U.I. that allows the user to adjust the length of the jump or modify the movement typology (i.e., ignoring the effect of gravity), thus limiting the user movements and the interaction with the model.
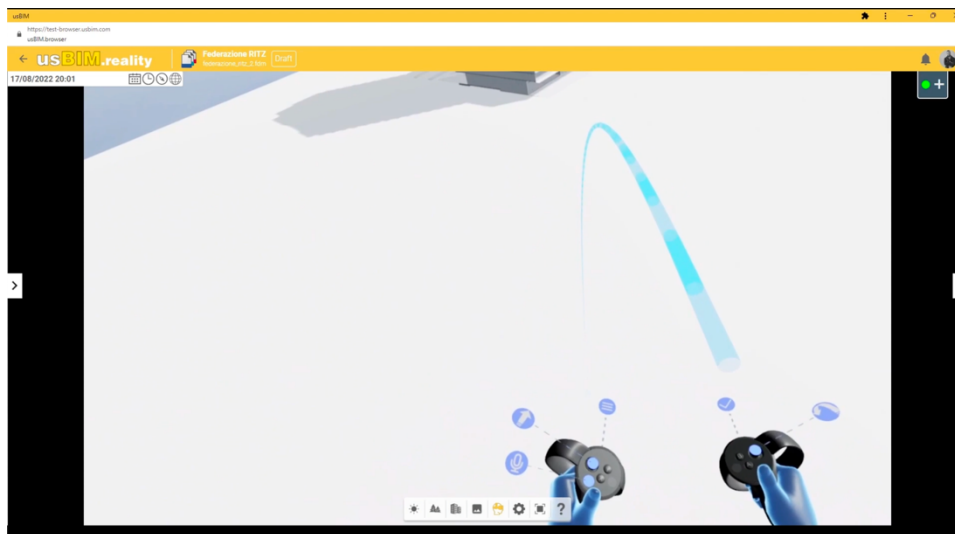

Figure 31 - Fixed jump length.

The **second** instance in this group regards again the interaction of the users with the software, once they are immersed in the Virtuality. Specifically, the found issues concern the general tools menu and its visibility during the model exploration. As it was previously highlighted, once the user is immersed in the Virtuality and the model exploration has begun, it is possible to gain access to a series of functions and tools, reachable through the main tools' menu. This menu is a fundamental part of the experience, as it represents the actual user interface of the software within the Virtual Environment and allows for the accessibility of all ancillary functions and utilities of usBIM.Reality.

To engage with the tool's menu, users have to press a specific button on the controller, recalling the visual aid that pops up in the form of an oleographic wheel around one controller (or both in case the user presses the button on the same controller). When the menu is not active, visual cues persist around each controller to inform the user about the buttons' function, facilitating the selection of the tool and consequentially easing the experience. Unfortunately, the feature described does not stay active for the whole duration of the experience. Instead, the visual cues disappear after the first tools menu activation, and the user is not given any option to recall them either via a sub-function or a setting (Figure 32). Thus, a "trial and error" routine takes place until familiarity is established with the buttons' functions

causing prolonged dead times during the model exploration, reducing the experience fluidity and the user's sense of presence.
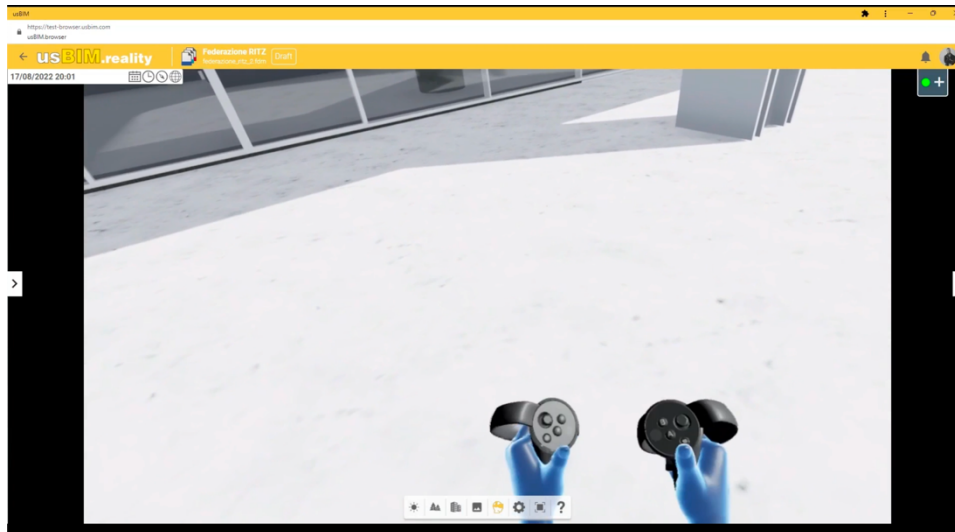

Figure 32 - Missing function icons on both controllers.

5.3.3 GROUP 3: MODELING ISSUES

The third group contains all the issues that concern the modeling aspects of the software, particularly related to the tolls that usBIM.Reality provides users to alter or modify the BIM model through the Virtual Reality experience directly in CDE. The four iterations conducted led to identify two issues that belong to this category, both classified during the second Iteration.

The **first** problem manifested during the interaction with one of the objects constituting the BIM model under review. The software usBIM.Reality integrates some of the functionalities of previously developed systems, specifically the capability of interacting with the model and implementing lasting BIM changes to the design, a feature derived from VRiBIM, the first Virtual Reality application developed by ACCA Software. Users can choose among several model interaction tools from the "Edit Object" menu, which is reachable via the Main menu wheel. Once the sub-menu is open on one controller, the other can be used to pick the item of the interaction, choosing the "Select Object" function and pressing the front trigger. Pointing the cursor toward the object and pressing the front trigger again initiates a third dedicated menu, presenting several functions which allow the user to "Delete", "Move", "Color alter", and "Insert" a BIM object to or within the Virtual Environment of the Model. Any of the interactions listed can be activated by pointing the cursor and pressing the front trigger. Depending on which tool has been selected, the software will return a different object behavior, i.e., show a set of control handles that let the user adjust the position of the selected object or make a portion of the selected object disappear. Regardless of which function is triggered, the Edit Object tools are useful during design review sessions,

as they allow the user to verify and potentially validate their design ideas in real-time. The issue found rests in the impossibility of reverting the action performed. Under no circumstances does the software allow the user to "change the idea" and go back (Figure 33) to the status of the object before the action. The issue is substantial as it limits the freedom of applying changes to the model, reducing the operability of the tool and the potential effectiveness of design reviews.

Figure 33 - No "go back" option in the Edit Object menu.

The **second** item of the group regards a recommendation for the implementation of an information management-specific tool. As it was pointed out before, usBIM.Reality offers several tools, and its integration into a CDE allows for bidirectional information flow (from and to the model) that multiple users can access at any given time. The accessibility of information is, in fact, a prominent aspect of usBIM.Reality development and is also at the center of any project management effort. The possibility of easily attaching project information or comments to BIM objects within the model during the Virtual Reality experience greatly enriches the information exchange process, as it gives other users the possibility of accessing the same information in real-time (or later, during a different experience). Unfortunately, the Beta version of the software does not incorporate any cues (visual or otherwise) that can lead users to identify objects presenting new or extra information effortlessly. A user could add a "note" to a wall or a window during a solo design review specifying the necessity for an intervention on the object, i.e., in the case of a clash, or implement additional information to the same object, like cut sheets of material, but no indication of the new property would appear on the object itself preventing other users from easily spot the item on their own. The inclusion of hints that can address the new or most recent model updates can be highly beneficial in terms of information flow and information management.

5.3.4   GROUP 4: GRAPHIC ISSUE

The fourth and last group contains the issues that concern purely graphic aspects of the software and that potentially alter or disturb the Virtual Reality experience. Throughout the four iterations conducted, only one issue was found to belong to this group.

The **first** and only specific problem identified refers again to the operation of the Measuring Tool and its interaction with the model. As previously discussed, this feature can be recalled from the Tools Menu as a sub-category of the Main menu and activated on either controller. The software informs the user about the beginning of the measuring process by turning the cursor into laser tape and projecting a set of two small concentric circles centered over a green dot, which represents the "aiming" of the measuring tool. As long as the function is active, the cursor and the aim remain in the form described, helping the user to define both ends of the measure better. Unfortunately, the Beta version of usBIM.Reality lacks graphic coordination between the two visual aids of the tool, and the aim is seldom correctly aligned with the cursor. Furthermore, the aim was found to disappear entirely in the process of taking several consecutive measurements as if it was stuck in the initial location. Additionally, after the measuring function is terminated or a new tool is engaged, the "aiming" symbol remains active, and it follows the user throughout the model as a magnet (Figure 34).
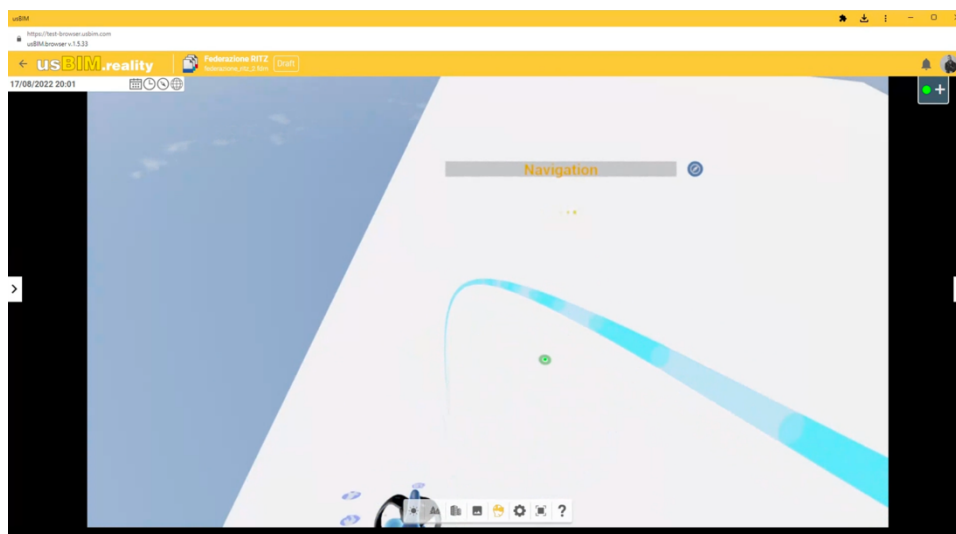

Figure 34 - Cursor aim is active when the tool is off.

5.4   SUGGESTIONS MATRIX PREPARATION (FOURTH STEP)

The conclusive portion of the research iterative processes is represented by the generation of the suggestion matrix for ACCA Software, where the found issues are collected, organized, detailed, and assessed in a compulsory document. The following paragraphs present the outcome of the data analysis conducted per each found issue separately. It focuses on the description and explanation of

the suggestions provided, and it is organized following the same breakdown as the previous chapter to ease the association and understanding of each item.

5.4.1   GROUP 1: PROGRAM LOGIC SUGGESTIONS

The **first** item of group 1 concerns the measuring tool and the quality of the measurements taken on the BIM model while in VR. Following the assessment of the issue, the research recommended the implementation of a color scheme system based on the cardinal axes (X, Y, and Z) to easily identify perpendicularity and parallelisms between the surfaces or points objects of the measurements.

It is well documented that measurements taken in Virtual Reality have a very high degree of accuracy with the corresponding physical ones [191] to the extent of equivalence, provided that such measurements can be properly taken. The suggested color code can be implemented to facilitate the visual understanding of the geometrical relationship between the parts and thus aid the user in measuring-taking and distinctness evaluation tasks.

Once the Measuring Tool is active and the first point of the measurement is fixed, the measuring line could change color while toggled by the user, identifying the resonance with one of the three cardinal axes, or visually informing the user about perpendicularity. I.e., the measuring line could turn to either red or green (Figure 35) If the measurement is taken parallel to the global axis "X" or "Y", shifting to blue when the measuring line is perpendicular to the horizontal plane (global axis "Z"). Furthermore, the software tool should implement a fourth "extra" color, i.e., purple, to highlight the perpendicularity of the two ending points of a measurement that does not lie on the horizontal or vertical global planes.

Figure 35 – Example: color code for geometric reference.

The **second** and **third** recommendations of this group are somewhat connected and highlight the importance of providing users with a tool for capturing and retrieving relevant instances concerning

the model visit and exploration, which might require attention or be referred to during later visits or uses. The software is currently implemented to serve also for design coordination and management purposes, and the possibility of framing a particular moment or situation as in a print screen might prove useful to help improve the workflow. I.e., users could be looking at a potential MEP or structural clash while in Virtual Reality and practically take a picture of the model conditions based on their P.O.V., using it at a later stage as a visual aid to show the identified problem and improve coordination clarity. The tool might be incorporated as an additional instance within the Tools sub-menu of the usBIM.Reality interface could be operated through one of the two controllers of the Meta/Oculus Quest 2. Once selected, the tool might remain in idle mode, like all other instruments offered by the program, and be switched on by pressing the lateral trigger of the active controller (Figure 36). Once the input is provided, both a visual and acoustic signal should manifest, and the software should capture the point of view of the user and allow for the selection of the file-saving destination via a dedicated pop-up window. The image and the storing location should be accessible by all users who participate in the experience during the current Iteration and future ones. Additionally, it is recommended to provide the option of saving the frame as part of the BIM data of specific model objects (ideally the subject/s of the coordination or clash detection), thus aiding the coordination and enhancing information management.

Figure 36 - Example: picture taken while in VR.

As mentioned before, the third recommendation is a direct consequence of the test about information accessibility performed on the model in the Virtual Environment (third Iteration), and it also relates to the execution of the functionality described above. Specifically, the users are given the possibility to access online BIM content directly from the VR through a dedicated tool, the activation of which currently leads to a software crash (as per the software version tested during the experiment). The function is operated via a sequence of specific in-VR steps. The Edit Object tool should be active on one controller, letting the user pick a BIM item via the "Select Object" function and then confirm the selection

using the front trigger. Once the BIM entity is highlighted, a secondary menu pops up, presenting the user with several additional functions to operate on the object. Namely, the user can change the aesthetics of the item, deleting or moving it and recall BIM information from the internet (which selection leads to the software crash). Provided the resolution of the bug in the code by ACCA Software programmers, the Recommendation matrix suggests implementing an extra tool in the secondary menu that visualizes as a "clip" and recalls all information stored in the selected object, granting the user the option of altering them or adding new ones (i.e., a picture taken during a model visit).

The **fourth** and **fifth** suggestions of the group are also interlinked as they both refer to the user interaction with the BIM model in the Virtual Environment. As explained in the literature, the DoFs associated with a Virtual Experience via the HMD used to explore the Virtuality are one of the key elements necessary to preserve a high sense of presence in the user [192]. The software of usBIM.Reality is currently designed to take advantage of the HMD and controllers' accelerometer and gyroscope, allowing the user to have a potentially seamless interaction experience with the BIM model in VR, but does not implement basic avatar movements such as pivoting and back-walking via controllers' joystick. In other words, the user's real-world movements fidelity is very high, but the software does not allow for bypassing them through in-VR controls, posing considerable challenges for stationary users, thus limiting the accessibility of the Virtual Environment and generating obstacles to the use of the Virtuality in small real-world settings. The Recommendation Matrix suggests overcoming the obstacles highlighted via the implementation of a "movements-controller" using one of the joysticks as an instrument. Should the Virtuality be experienced via an HMD that presents two controllers, the software could request the user to select one of them at the beginning of the interaction to associate the movements-controlling to the related joystick and have it aiding or bypassing the accelerometer instructions in specific scenarios. The same shall apply In the case of an HMD with only one controller, with the difference that no preference would be requested from the user. The Recommendation matrix also highlights the importance of maintaining a clear distinction between the movements allowed via the joystick and the ones regulated by the HMD accelerometer, limiting the override of the former over the latter to prevent the risks of motion sickness. Specifically, it is clarified that in the case of a user walking forward in the real world, the software shall not allow for the joystick to bypass the movement picked by the HMD accelerometer and have the avatar walk back words. Coordination and coherence of movements must be guaranteed and maintained throughout the experience.

The **sixth** recommendation aims at facilitating and quickening the movements of the avatar within the Virtual Environment while improving and aiding on-the-model design coordination meetings and interaction among stakeholders. The Tools Menu currently presents the "Change location" function that allows the user to select a "pre-saved" portion of the federated BIM model and instantly transfer the avatar to that location. Such a tool requires the team to pre-define areas of potential interest and save them as information while federating several BIM models (might that be MEP and structural portions or different parts of the same architectural model). Unfortunately, the system does not allow for new areas

of interest to be registered for use once the model is fully virtualized, making the exploration and coordination on large models (such as the case study) more challenging. The matrix suggests the implementation of a new feature to overcome the obstacle, consisting of a new set of movements for the avatar based on the use of both controllers. It is recommended to mimic the 3Dmodeling software and script a function that allows to "zoom" in and out of the user's POV, also providing the option to rotate it around the model on the vertical axis via a fixed point (ideally, the model geometrical barycenter). The function could be accessed via the "Navigation Menu" through the Main menu and be initiated using a combination of controller buttons. I.e., referring specifically to the Oculus/Meta Quest 2 controllers, once the tool is in idle mode, users could press and hold the lateral trigger on one controller to initiate the function and use the joystick of the same controller to zoom the POV in or out (joystick forward brings the model closer, joystick backward distances the model). The joystick on the other controller can be used to complete the sequence moving left or right and subsequentially rotating the model clockwise or counterclockwise. Once the desired position is reached user can let go of the lateral trigger, close the function, and "jump" back into the model using the appropriate tool. Most notably, the recommendation provided refers to the shifting and rotation of the user's POV. Thus, it is not the model to alter its gematrical location compared to the user; Instead, it is the user who modifies the position of the avatar in respect of the model. Such distinctions are important as they prevent the function from affecting other avatars' locations on the model during multi-user coordination meetings.

The **seventh** and last suggestion of this group concerns the time required for the initiation of the model in the Virtual Environment and the use that it can be made of the related downtime. Once usBIM.Reality is started via the dedicated icon in the usBIM.Browser interface, the software requires a certain time frame to load the model and the virtual space fully. Once the function is activated, the user is immediately transferred into the Virtual Environment that appears empty, as the model is slowly generated through federation and rendering. The downtime spent waiting for the operation to be completed depends on several factors, but it is mostly related to the power of the hardware and the strength of the internet connection, and it can take up to some minutes (the longest registered downtime was 2 minutes).

Additionally, provided the differences in hardware and connection of alternative setups in multi-user scenarios, stakeholders might experience uploading delays and initial lags and simply manifest in the Virtual Reality later than most, although initiating the experience at the same time. The recommendation provided to ACCA Software suggests making use of the loading time and implementing a downtime area in the form of a virtual room (Figure 37) where all users can be located simultaneously after the initiation of the Virtual Reality experience and wait for the model loading and rendering completion. The in-between space can also function as a pre-coordination or kick-off situation, especially in the case of a project presentation to external or new stakeholders. Once the model and the Virtual Environment are fully rendered and the BIM is loaded, the software shall signal the completion (visually and acoustically) to the users who can decide to be transferred to the model or remain in the room longer to complete ongoing processes (i.e., the pre-coordination discussion).

Figure 37 - Example: the waiting room for model rendering and pre-coordination.

5.4.2 GROUP 2: USER INTERFACE (U.I.) SUGGESTIONS

The **first** recommendation of the group concerns the visibility of the menu and tools button indications on the virtual controllers and the visual description of their functions throughout the Virtual Experience. Once immersed in Virtuality, the user can see descriptive icons surrounding both controllers that provide insights into which functions and tools each button or trigger gives access to. A light-blue shadow hovers on top of each controller's active portion and is visually connected to an icon of the same color that describes the overall function and use of that element. The information is useful as it helps guide the user's decision and actions on the model, not only in the case of a first-time experience, but also for more advanced users. After the first command or action is initiated, the "ghost" indications disappear, and the user cannot re-activate the visualization for the rest of the experience. Such a setback reduces the ease of use of the program and potentially prejudices the user's sense of presence [190].

On the other hand, having the function icons constantly active might be distracting and lead to the same outcome. Thus, the implementation of a menu function that allows for an "always on or always off" type of setting does not resolve the inconvenience. To overcome the problem, the Recommendation Matrix suggests implementing a "light touch" time-sensitive script in the software code that would allow users to re-activate the icons visualization when needed by gently holding down a specific button of any of the two controllers. The icons might remain visible until a tool is selected, disappearing while the action is performed and then re-appear once the function is concluded. The software shall allow the user to hide the "ghost icons" by pressing again the same controller button in the same fashion used to activate the function (one touch on, one touch off) to avoid any distracting effect previously described.

The **second** and last suggestion of this category, provided by the matrix, concerns an existing tool of the software, specifically the jump function and its characteristics. Currently usBIM.Reality does not offer

any option for modifying the trajectory and length of the movement performed, limiting the tool's functionality. When visiting large projects like the case study, It might become useful to adjust the length of the jump (Figure 38) to reach longer or higher with one single movement, avoiding multiple jumps that might result in unprecise avatar positioning, consequently requiring extra time and efforts on the model and lowering the comfort and potential effectiveness of the experience. It is important to highlight that the recommendation does not read as implementing a jump function of infinite length or a tool for calculating ahead the distance the avatar shall reach within one jump (similarly to the already described measuring tape tool).

On the contrary, the suggestion suggests creating a three-category option window within the Navigation Menu to let the user choose between three distinct lengths (ideally 50, 15, and 5 meters) that the jump tool can reach. Once the user visits the Navigation Menu, the options window might appear, offering to pick one of the three solutions that remain the active choice until a different jump length is selected via the same procedure. Implementing this recommendation might result in a considerable increment of software operability if applied in parallel to the potential development of a new tool for zooming in and out of the model.
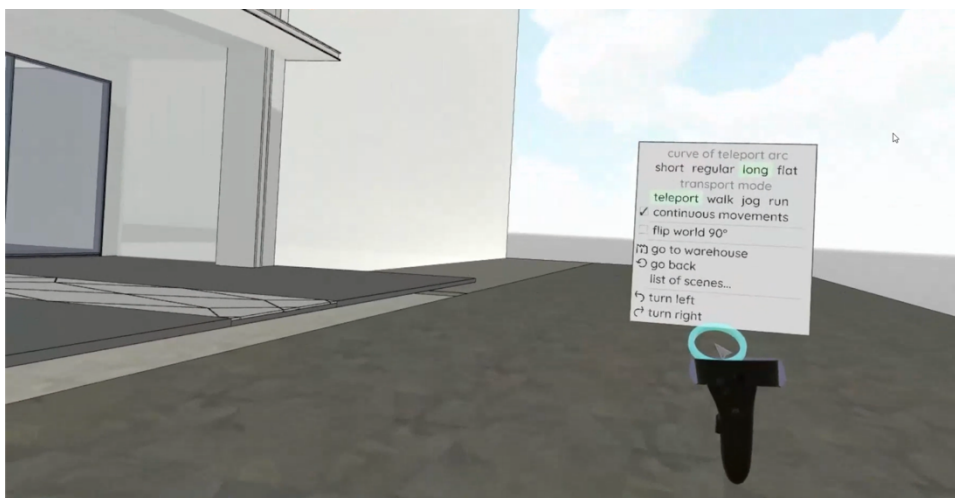

Figure 38 - Example: adjusting the jump length.

5.4.3 GROUP 3: MODELLING SUGGESTIONS

The **first** item of this group regards specifically the modelling functions offered by usBIM.Reality, via the Edit Object Menu. The program, in fact, lets users operate specific types of alterations to the model and the BIM objects contained in it. As previously described, the tools in the dedicated menu can change some aesthetic properties of the model (i.e., modify the texture of an object or its color), delete a specific portion of it (after selecting the object itself), and potentially add BIM objects or information from the internet. These functions are particularly useful during design coordination as they allow stakeholders to verify design options in real-time potentially. To produce any alteration, users have to select the

object via the dedicated tool in the Edit Object Menu and confirm the choice by pressing the front trigger on the controller. Subsequentially, the software requests to pick which type of change to apply, i.e., deletion, and after the front trigger confirms again, the operation is performed. The software, unfortunately, does not offer any tool to revert the changes or alteration operated. Thus, anything done on or to the BIM objects of the model is definitive. The matrix suggests creating a "go back" option that lets users correct eventual misuses of the editing tools or simply return to the object's pre-alteration status should the change not match the expected outcome. It is proposed to use one of the buttons on the active controller, ideally the lateral trigger, that, once pressed, simply cancels the last action, reverting the object to its initial state. The "go back" tool should apply if the Edit Object tool is active and on the active controller only to avoid any overlapping of functions-buttons relations. In this way, users do not cancel previously implemented changes by themselves or other stakeholders.

The **second** and last suggestion advanced by the matrix concerns another aspect of the design coordination process, specifically, notes-taking and mark-ups. A fundamental aspect of design review is represented by the sketches, notes, and revision clouds generally implemented on the drawings during focus meetings and serve as a guide for designers during their project updates [193]. Although usBIM.Reality allows for multi-user interaction within the Virtual Environment of the BIM twin, the software does not possess any tool that provides stakeholders the ability to comment on and review the design of the project actively. Considering the importance of the design coordination process, It might be advisable to implement a dedicated function in this regard (Figure 39).

Figure 39 - Example: mark-up tool in VR.

Given the nature of the suggested tool, this new instrument should be located in the Tools Menu as stand alone. The core principle is to let users add comments (in the form of written text or voice notes) to selected BIM objects or model parts for real-time coordination or future references. The tool might be activated by recalling it from the Tools Menu through the Main Menu; once the instrument is loaded

on one controller, the user can point it to the object that requires review and press the front trigger, initiating the comment generation process. At that point, the user should then be prompted to specify the note, generating it either via voice recognition or virtual keyboard, and once the note is complete, the function can be closed by pressing another specific button of the active controller, i.e., the lateral trigger. The generated mark-up shall be automatically linked to the object as additional BIM information and accessible by any other stakeholder granted permission on the model, who can understand the presence of the comment via a visual cue on the object itself (i.e., the object might change color do highlight the presence of a note).

5.4.4 GROUP 4: GRAPHIC SUGGESTIONS

The **first** and only recommendation that the Matrix issues for this group aims at correcting a minor inconvenience in terms of difficulty or challenges posed for its resolution, but that documented with such a frequency that it proved impactful for the fluidity of the iterations.

Whenever the user activates a tool on one of the controllers, the software responds with a visual cue that signals the function is idle. I.e., when the jump function is activated, the user will see an arch protruding from the controller, mimicking the distance of the movement and highlighting the end point of the jump. The large majority of the tools, when idle, project a green marker in the shape of a bull's eye onto the model that moves following the movements of the active controller, helping the user understand where the function will take place and which object it will affect. Unfortunately, the pre-release of usBIM.Reality uses an actual virtual object as a marker, and an issue with the code makes the bull's eye persist on some object after the conclusion of the operation. The presence of a misplaced marker or, in some cases, multiple ones lead to confusion and uncertainty about the correctness of the selection. The suggestion is to substitute the marker and its virtual equivalent with a color code highlight indicating to the user which object is currently targeted for the operation, thus avoiding misplacing the action due to unprecise selection.

5.4.5 MATRIX SUMMARY

The suggestion matrix prepared for ACCA Software outlines key findings and recommendations for improving the proprietary Virtual Reality software usBIM.Reality and its tools and functionalities.

These recommendations aim to enhance the usability, functionality, and user experience of ACCA Software's VR tools and improve design coordination, measurement accuracy, and overall workflow efficiency.

The suggestions generated are collected into four major categories and present five key outputs that should be considered the outcome of the analysis conducted:

- Implementation of a Color Scheme System: The research recommends implementing a color scheme system based on the cardinal axes (X, Y, and Z) to easily identify perpendicularities and parallelisms between surfaces or points in the BIM model during VR measurements. This color

scheme aims to facilitate the visual understanding of the geometrical relationship between parts and aid users in measurement-taking and evaluation tasks.

- Tool for Capturing and Retrieving Relevant Instances: The Matrix presents the importance of providing the users with a tool for capturing and retrieving relevant instances during model visits and explorations, which can be referred to during later visits or uses. This tool is intended to help improve workflow, particularly for design coordination and management purposes.
- Clear Distinction Between Movements: The Suggestion Matrix emphasizes the importance of maintaining a clear distinction between movements allowed via the joystick and those regulated by the Head-Mounted Display (HMD) accelerometer in VR experiences. The recommendation aims to prevent the risks of motion sickness and ensure coordination and coherence of movements throughout the VR experience.
- Implementation of a Dedicated Function for Design Coordination: It is recommended to implement a dedicated function for actively commenting on and reviewing the design of the project within the VR environment. The function associated with the suggestion is crucial for enhancing the design coordination process and facilitating notetaking and mark-ups.
- Access to Online BIM Content: The Matrix suggests the implementation of a tool that allows users to access online BIM content directly from the VR through a dedicated tool. This tool should provide the option to alter or add new information to selected BIM objects, such as adding pictures taken during a model visit.

6 CONCLUSIONS & FUTURE WORKS

6.1   CONCLUSIONS.

The Ph.D. thesis presents an overview of research aimed at developing a Recommendation Matrix to refine and enhance the beta version of usBIM.Reality. This proprietary Virtual Reality (VR) application, created by the Italian software house ACCA Software, is designed to integrate with another proprietary system from the same company, the Cloud platform known as usBIM.Browser.

Driven by the recognition of the increasing significance of Extended Reality (XR) technologies in the Architecture, Engineering, and Construction (AEC) industry, this research is supported by a literature review that explores the successful integration and implementation of XR-BIM technologies in actual case scenarios. This review includes AEC education, design, construction, and post-construction processes, highlighting the potential of VR, Mixed Reality (MR), and Augmented Reality (AR) to improve project management, collaboration, and visualization. With the proven support of these technologies for the AEC industry, the study aims to enhance the usability, functionality, and user experience of usBIM.Reality a proprietary VR software created by ACCA Software and deployed on the common data environment, usBIM.Browser, also developed by the same company. Specifically, the research seeks to improve the software's design coordination, measurement accuracy, and overall workflow efficiency. The research was conducted in collaboration with ACCA Software's R&D department and other stakeholders involved in designing a twenty-two-story residential building in Dubai (UAE), which served as a case study. The research employs an empirical approach focusing on practical application and direct experimentation rather than theoretical exploration, leading to an iterative process divided into four major steps.

The research began with a thorough analysis of the hardware specifications needed to operate the software provided by ACCA Software's R&D. Initially, it focused on configuring a setup capable of meeting the VR application's intensive computational demands. The correct setup was vital for the effective rendering of the VR experience, given its high graphic requirements. Special attention was given to comparing and selecting the best GPU and CPU for the tasks ahead, resulting in the preparation and initial testing of two hardware configurations. Ultimately, an assembled Intel® NUC11 i9 with a dedicated GeForce RTX™ 3060 GPU was selected, along with the Oculus/Meta Quest 2 as the best HMD apparatus.

Following the hardware setup, the study's second step involved evaluating the VR software through several visits and design coordination sessions within a six-month period, using the BIM-twin of the case study. These iterative visits identified a total of 12 items, including software issues and areas for potential improvements, such as the inability to determine geometrical relationships between measurements and the surfaces referred to or the lack of "back walking" and "POV turning" in VR using the controllers' joysticks. The exploration and testing sessions categorized the necessary interventions into four groups: program logic, user interface, graphic presentation, and modeling capabilities. In the

third iterative step, to each item listed an intervention priority level was assigned to help ACCA Software's development team gauge the urgency of implementation from the users' perspective.

The analysis of the VR software underscores the potential of combining VR and BIM technology, as discussed in the literature review. The research highlights that VR enables a significantly enhanced level of project and design understanding compared to traditional coordination meetings. Moreover, although incomplete or partially faulty, some of the tools of the software demonstrated the high effectiveness of leveraging BIM aspects of the model during a virtual visit and the consequent possibility of anticipating construction issues as well as improving design information accessibility (i.e., the linkage of external data such as cut-sheet information to a single BIM item and its retrieval in VR).

The analysis of data collected over the four iterations, the categorization of issues, and the creation of a priority scale culminated in the fourth and final phase, leading to the generation of suggestions to solve or mitigate each issue. Recommendations included among others, implementing a color scheme system to address measurements, a tool for capturing and retrieving relevant instances directly in VR, enhancing user's movement in relation to the interaction with the Virtual Enviroment, the implementation of dedicated functions for design coordination, and access to online BIM content.

In terms of numbers, Program Logic is the group that presents the higher concentration of recommendation, showing seven items out of the total twelve, while Modeling is the category with the lowest number of found issues, presenting only one item. The result is not surprising; It was expected that the majority of improvements would have originated in the sphere associated with how the software works and operates, provided its Beta state at the time this research was conducted. Nevertheless, it shall be noted that all suggestions provided within this group are mild adjustments to a system that was already strongly efficient. Only two out of the seven issues were marked as critical with a priority of 5, and neither of them is expected to trigger important coding efforts or present actual implementation challenges from the R&D department. Interestingly, the item with the lowest degree of priority also belongs in this group.

The already elevate proficiency of the software is also manifested via the limited number of critical priorities identified. Only three out of the total twelve recommendations present a score of 5, while the majority of the items marks between 3 and 4.

The culmination of this research is the Recommendation Matrix, that was constructed throughout the iterative processes previously described. The document collects the different issues in groups and assesses each problem through a visual and written descriptions while also providing a criticality scale and an recommendation about a potential solution through examples. This feedback tool is designed to assist ACCA Software in integrating these recommendations into the final product version.

The research's key findings highlight the significant advantages of VR in enhancing design management practices and offering innovative solutions to longstanding industry challenges. This thesis contributes to the ongoing development of VR applications in the AEC sector, paving the way for

future research and practical implementations that leverage extended reality technologies to advance design and construction methodologies.

6.2 FUTURE WORKS.

The study underlines the ongoing need for advancements in specific features of VR software to enhance performance from the final user's perspective, and it sets the stage for future investigations into the development and implementation of XR-BIM systems by shedding light on possible avenues for future research, particularly in the domain of eXtended Reality (XR) technologies, emphasizing the importance of further exploration in developing XR-BIM systems for Common Data Environments (CDE).

The collaboration among these platforms can be expected to rise in the near future due to the democratic nature of the CDEs, which act as interactive cloud and computing platforms capable of hosting, maintaining, and providing access to any sort of information uploaded within. Common Data Environments are, in fact, not limited by the restriction of file formats and, thanks to WebSocket connection protocols, provide persistent bidirectional, real-time, event-driven communication between "clients" and "servers". When paired with an information-rich structure such as a BIM model, CDEs represent the next frontier for the AEC industry, providing the means to reduce the cumbersome processes related to the pre-contract (design) stage as well as the possibility of ease and facilitate the project information access during and after construction.

Using CDEs as the base platform for the entire project workflow management allows stakeholders a higher level of control over the outcome with a considerably lower effort level and time-spending than the current practice. The possibility of working and collaborating simultaneously via the cloud on the same BIM model will soon be uplifted by the addition of information streamlining to all forms of XR at once.
To exemplify, it can be expected that future works will address XR-BIM-CDE platforms that grant stakeholders on-site access to BIM information via Mixed Reality Headsets for clash detection, while designers situated in the office implement related changes to the model via regular computer screen and other stakeholders perform a client presentation of the performed project alteration to get the final approval, all in real-time.

It can be then envisioned that future research will focus on protocolling and developing integrated BIM-CDE that allows for the simultaneous use of different forms of XR on the same project model, translating into the possibility of accessing the same information of the same project from different locations via different XR mediums and granting simultaneous cooperation among stakeholders.

7 GLOSSARY

To ensure more fluid and precise reading, it has been decided to provide a quick glossary/reference list in bullet points to clarify the meaning of acronyms in the document's paragraphs.

- *Advanced technology* = A technology that is still immature but promises to deliver significant value or has some technical maturity but still has relatively few users. Examples are artificial intelligence, bot agents, speech and handwriting recognition, virtual Reality and 3D visualization, smart cards, real-time collaboration, enhanced user authentication, data mining, and knowledge management.[194]
- *A.I. | Artificial Intelligence* = It is the science and engineering of making intelligent machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but A.I. does not have to confine itself to biologically observable methods. [195]
- *IoT | Internet of Things* = A type of network to connect anything with the Internet, based on stipulated protocols through information sensing equipment to conduct information exchange and communications in order to achieve smart recognitions, positioning, tracing, monitoring, and administration. [196]
- *XR | Extended Reality* = It refers to all virtual environments generated by computer graphics and wearables. The "X" in XR is simply a variable that can stand for any letter. XR is the umbrella category that covers all the various forms of computer-altered Reality, including Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR). [18]
- *VR | Virtual Reality* = The use of computer modeling and simulation that enables a person to interact with an artificial three-dimensional (3-D) visual or another sensory environment. [197]
- *MR | Mixed Reality* = It is an overlay of synthetic content that is anchored to and interacts with objects in the real world in real time. Mixed Reality experiences exhibit occlusion in that the computer-generated objects are visibly obscured by objects in the physical environment. [17]
- *AR | Augmented Reality* = A live, direct, or indirect view of a physical, real-world environment whose elements are augmented by computer-generated sensory input. [16]
- *AEC | Architecture Engineering and Construction* = The sector of the construction industry that provides services on architectural design, engineering design, and construction services. [3]
- *BIM | Building Information Modeling* = BIM is a set of digital tools and processes that helps the AEC industry manage projects effectively by improving the planning process, design, and other activities in construction. [198]
- *CDE | Common Data Environment* = A CDE is a cloud-based space where information from construction projects is stored and accessible to project participants. This access depends on participants' requirements or level of authorization, as well as their contractual obligations [199].
- *LOIN | Level Of Information Needed* = It is a framework that defines the extent and granularity of information to be produced and delivered in accordance with the standards of ISO [200]

- *LOD | Level Of Development* = Level of development (LOD) is a set of specifications that gives professionals in the AEC industry the power to document, articulate, and specify the content of BIM effectively and clearly. [201]
- *IFC | Industry Foundation Class* = IFC is a standardized, digital description of the built asset industry. It is an open, international standard and promotes vendor-neutral, or agnostic, and usable capabilities across a wide range of hardware devices, software platforms, and interfaces for many different use cases. [202]
- *GPU | Graphics Processing Unit* = A GPU is a processor designed to handle graphics operations. This includes both 2D and 3D calculations, though GPUs primarily excel at rendering 3D graphics.[181]
- *HDM | Head Mounted Display* = They are small displays or projection technology integrated into eyeglasses or mounted on a helmet or hat. Heads-up displays are a type of HMD that does not block the user's vision but superimposes the image on the user's view of the real world.[75]
- *DoF | Degree of Freedom* = Relating to VR, it is used to explain how an individual can move in a headset and the number of axes that are tracked [203].
- *Sense of Presence* = one's sense of being in the virtual world. The illusion is perceptual but not cognitive, as the perceptual system identifies the events and objects, and the brain-body system automatically reacts to the changes in the environment, while the cognitive system slowly responds with the conclusion that what the person experiences is an illusion [204].
- *4IR | Fourth Industrial Revolution* = is the next phase in the digitization of the manufacturing sector, driven by disruptive trends, including the rise of data and connectivity, analytics, human-machine interaction, and improvements in robotics [205].
- *FPS | Frame per second* = Frames per second (FPS) is a unit that measures display device performance in video captures and playback and video games. FPS is used to measure frame rate— the number of images consecutively displayed each second — and is a common metric used in video capture and playback when discussing video quality [206].
- *Accelerometer* = A device that detects acceleration and tilt. Built using MEMS technology, accelerometers detect impact and deploy automobile airbags, as well as retract the hard disk's read/write heads when a laptop is dropped. It also enables, i.e., a handheld display to be switched between portrait and landscape modes when the unit is turned [207].
- *Gyroscope* = A device used to maintain orientation with the earth. It is used in airplane and vehicle navigation systems as well as game controls such as the Wii from Nintendo. Smartphone and tablet gyroscopes detect changes in orientation from portrait to landscape. A gyroscope contains three different-sized rotating rings (gimbals) connected at two points, with the smaller inner ring rotating around a spinning disc. While the speed of the spinning disc maintains its direction, the rings are free to move on their axes, and their movements are measured [208].
- *Spatial awareness* = The ability to understand the relationship between one's movements and the objects in one's surrounding environment. It is also referred to as spatial perception, and it essentially gives people the ability to avoid running into things around them while moving [209].

- *Program Logic* = Instructions in a program arranged in a prescribed order to solve a problem [210].
- *UI | User Interface =* The way a person interacts and commands a computer, tablet, smartphone, or other electronic device. The user interface (UI) comprises screen menus and icons, keyboard shortcuts, mouse and gesture movements, command language, and online help [211].

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9 APPENDIX

PRJ PHD IUAV XXXVI CYCLE_Nicolò M. Bressan
IUAV   ACCA usBIM.Reality ASSESSMENT MATRIX

Item number	Typology of comment	Comment	Comment's Priority	Reference	Notes
1	Program Logic	Once the laser tape is selected, it is possible taking measures directly on the BIM via VR. No clear marker/indication allows the user to visually understand if the measurement is perpendicular to the origin point.	5	https://iuavit-my.sharepoint.com/personal/nmbressan_iuav_it/Documents/PRJ-PHD%20IUAV%20XXXVI%20CYCLE/2022-2023/1_Project%20files/2023%2002%2010_Test%201/1_rev01.mp4	A color code could be implemented that identifies the perpendicularity given the origin point.
2	Program Logic	It would be helpful to "save" a view as a location point to re-visit the same with other stakeholders. Furthermore, the software does not offer a "snapshot" tool to take a screenshot directly within the VR environment for future use/reference.	5	https://iuavit-my.sharepoint.com/personal/nmbressan_iuav_it/Documents/PRJ-PHD%20IUAV%20XXXVI%20CYCLE/2022-2023/1_Project%20files/2023%2002%2010_Test%201/4_rev00.mp4	It would be helpful to have the option of "print-screen" the POV to facilitate stakeholder coordination.
3	Program Logic	The loading of external media/items onto the model directly from VR is not implemented. The software crashes when importing an object from ACCA online repository.	4		
4	Program Logic	The backward walk is currently not implemented through the use of the left joystick. It presents a challenge for actual model exploration In VR if seated.	4	https://iuavit-my.sharepoint.com/personal/nmbressan_iuav_it/Documents/PRJ-PHD%20IUAV%20XXXVI%20CYCLE/2022-2023/1_Project%20files/2023%2002%2010_Test%201/8_rev00.mp4	It might be useful to implement the backward walk to facilitate overall movements within the VR experience.
5	Program Logic	POV rotation is not possible but through the HMD's accelerometer. It presents a challenge for actual model exploration In VR if seated or limited in movement.	4	https://iuavit-my.sharepoint.com/personal/nmbressan_iuav_it/Documents/PRJ-PHD%20IUAV%20XXXVI%20CYCLE/2022-2023/1_Project%20files/2023%2002%2010_Test	It might be useful to implement the POV rotation via Joistick
6	Program Logic	It could be helpful to implement a function for the easy repositioning of the avatar/user-POV within the model virtual environment	2		in this example, SKETCH VR allows for a jump-off of the mode, making the re-positioning easier.
7	Program Logic	It could be useful to implement a "waiting room" to allow for the full and final loading of the model, which can also be used as meeting room to kick off the coordination on the model.	1		in this example, SKETCH VR allows us to visually appreciate the status of the VR experience upload. Dead waiting times are eased up, and the understanding of the time required is explained graphically. The feature has an impact on stakeholders who need to become more familiar with VR. It is also serving as "jump-back" for the relocation on the model.
8	U.I.	Once the user begins the experience, the several menus and action tools are no longer visible and easy to address as they are at the starting point. It might create confusion for stakeholders visiting the model with the consultant, potentially breaking the fluidity of the experience.	5	https://iuavit-my.sharepoint.com/personal/nmbressan_iuav_it/Documents/PRJ-PHD%20IUAV%20XXXVI%20CYCLE/2022-2023/1_Project%20files/2023%2002%2010_Test%201/2_rev01.mp4	Implementing a "light touch" feature that allows the commands to pop up their names when the related buttons are touched on could be interesting. Alternatively, command tags can remain visible throughout the experience.
9	U.I.	The teleportation distance is fixed, and no command tool allows the user to adjust the length of the jump, neither visually nor numerically. It might generate issues during the experience of bigger models.	4	https://iuavit-my.sharepoint.com/personal/nmbressan_iuav_it/Documents/PRJ-PHD%20IUAV%20XXXVI%20CYCLE/2022-2023/1_Project%20files/2023%2002%2010_Test%201/3_rev01.mp4	It would be helpful to have the option to extend or reduce the jump length via UI input
10	Modeling	It would be helpful to implement a "go back" command to revert design actions.	3	https://iuavit-my.sharepoint.com/personal/nmbressan_iuav_it/Documents/PRJ-PHD%20IUAV%20XXXVI%20CYCLE/2022-2023/1_Project%20files/2023%2002%2010_Test%201/9_rev01.mp4	In this example, SKETCH VR allows for the modification and changes of the model with a direct link through VR. It also allows for reverting all actions perfomed on the model.
11	Modeling	It could be helpful to add an "annotation feature" that allows for quick and direct communication of potential design issues or to facilitate the highlighting of clashes during clash detections.	2		in this example, SKETCH VR allows drawing on the model to immediately highlight to the other stakeholders the found prblem. It is a qucik access tool.
12	Graphic	Measurements indicators remain on the model during the experience and are visible as see-through.	3	https://iuavit-my.sharepoint.com/personal/nmbressan_iuav_it/Documents/PRJ-PHD%20IUAV%20XXXVI%20CYCLE/2022-2023/1_Project%20files/2023%2002%2010_Test%201/6_rev00.mp4	

Figure 40 – ACCA Software Recommendations Matrix

10 AKNOWLEDGMENT