DEVELOPMENT AND VALIDATION OF BIM-BASED NATURAL USER INTERFACES FOR NON-GEOMETRICAL INFORMATION MANAGEMENT

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À memória da minha Mãe.

A journey of a thousand miles begins with a single step.

Lao Zi

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ABSTRACT

Innovation and the adoption of new processes are transversal phenomena across industry sectors. As technology progresses, current paradigms adjust, which may disrupt more traditional approaches and processes. In particular, the Architecture, Engineering, Construction and Operations (AECO) sector is not immune to the change of technological cannons and paradigm shifts. Such changes can be illustrated by the gradual uptake of Building Information Modelling (BIM), although reportedly slower than originally expected. Indeed, and despite the known advantages of the adoption of BIM (e.g., enhanced visualisation and access to information, benefits to management of costs and deadlines, as well as maintenance, among many others), the AECO sector still faces the absence of a full-fledged acceptance of the BIM methodology, providing the opportunity for further developments in the way of interacting, accessing and exchanging project-related information. Therefore, to promote more generalised access to BIM and an enhanced understanding of the methodology by a wider range of AECO professionals, further research on innovative interfaces attuned to the tasks, requirements, and working environments of AECO professionals is in need.

Considering the positive impacts of Natural User Interfaces (NUIs) in the AECO sector verified in recent applications, especially those based on Virtual Reality (VR) or Augmented Reality (AR), the present thesis aims to explore the relationships between these technologies and BIM. Additionally, this thesis intends to provide a clear overview of the applications of BIM-based VR and AR interfaces and develop more natural approaches to interact, manage and enrich BIM models' information. Moreover, this study aims at shedding light on recommendations and guidelines for a usability methodology to assess the suitability of the proposed solutions.

The research developed comprises three systematic reviews addressing the core body of knowledge related to the acceptance and usability of innovative interfaces and the management of non-geometric information. In particular, two systematic literature reviews on the impacts, best practices, and current knowledge on the application of BIM-based VR and AR, and a literature review of the developments concerning Semantic Enrichment (SE) and BIM.

Additionally, two immersive interfaces were developed to provide access to BIM information through task-driven applications suitable for users with different backgrounds and levels of expertise. In detail, the workflow and laboratory assessment of a proof of concept coupling VR and laser scanning is presented. To overcome the obstacle to proper communication between project-related entities. This preliminary interface provided a starting point for developing more complex systems for the semantic enrichment of BIM models.

The developing stages of a second VR interface for semantic enrichment are described. These include the presentation of a straightforward openBIM approach to import BIM models into a game engine while maintaining the models' semantics and geometry and the possibility of validation through Information Delivery Specifications (IDS).

A thorough usability assessment is detailed, including formative and summative evaluations, as well as the feedback gathered from 62 interviews with 31 AECO professionals. The results show that users with no previous knowledge can interact with BIM models, even those lacking a deep understanding of BIM methodology or experience with BIM authoring tools (83,9% of participants). Indeed, most participants were able to manage BIM information naturally in the VR environment, reaching a usage close to that expected from a more experienced user. Additionally, perceived satisfaction demonstrates a general liking and consent for applying the proposed approach to facility management tasks, even amongst participants with no previous VR and/or BIM experience.

KEYWORDS: Building Information Modelling, Semantic Enrichment, Natural User Interfaces, Virtual Reality, Augmented Reality, Usability.

RESUMO

A inovação e a adoção de novos processos são fenómenos transversais a todos os sectores industriais. À medida que a tecnologia avança, os paradigmas atuais ajustam-se, podendo perturbar abordagens e processos mais tradicionais. Em particular, o sector da Arquitectura, Engenharia, Construção e Operações (AECO) não é imune à mudança de cânones tecnológicos e de paradigma. Tais mudanças podem ser ilustradas pela adopção gradual do Building Information Modelling (BIM), embora alegadamente mais lenta do que inicialmente esperado. De facto, e apesar das vantagens conhecidas da adopção do BIM (e.g., melhor visualização e acesso à informação, benefícios para a gestão de custos e prazos, bem como manutenção, entre outros), o sector AECO revela ainda a ausência de uma aceitação plena da metodologia BIM, proporcionando a oportunidade de novos desenvolvimentos na forma de interacção, acesso e troca de informação relacionada com projectos. Desta forma, para promover um acesso mais generalizado ao BIM e uma melhor compreensão da metodologia por um maior número de profissionais do sector AECO, é necessária mais investigação sobre interfaces originais em sintonia com as tarefas, requisitos, e ambientes de trabalho dos profissionais.

Considerando os impactos positivos das Interfaces Naturais ou *Natural User Interfaces* (NUIs) no sector AECO verificados em aplicações recentes, especialmente aquelas baseadas em Realidade Virtual (RV) ou Realidade Aumentada (RA), a presente tese visa explorar as relações entre estas tecnologias e o BIM. Adicionalmente, esta tese pretende fornecer uma visão clara das aplicações de interfaces de RV e RA baseadas em BIM e desenvolver abordagens mais naturais para interagir, gerir e enriquecer a informação dos modelos BIM. Este estudo visa também clarificar recomendações e orientações para uma metodologia de usabilidade que permita avaliar a adequação das soluções propostas.

A investigação desenvolvida compreende três revisões sistemáticas que abordam o corpo central de conhecimentos relacionados com a aceitação e usabilidade de interfaces inovadoras e a gestão de informação não geométrica. Em particular, duas revisões sistemáticas da literatura sobre os impactos, melhores práticas, e conhecimentos actuais sobre a aplicação de interfaces de RV e RA baseadas em BIM, e uma revisão da literatura sobre os desenvolvimentos relativos a Enriquecimento Semântico (ES) e BIM.

Além disso, foram desenvolvidas duas interfaces imersivas para fornecer acesso a informação BIM através de aplicações orientadas para tarefas e adequadas a utilizadores com diferentes antecedentes e níveis de especialização. Em detalhe, é apresentado o fluxo de trabalho e a avaliação laboratorial de uma prova de conceito conjugando RV e *laser scanning* para superar o obstáculo da comunicação inadequada entre entidades envolvidas em projectos de construção. Esta interface preliminar proporcionou um ponto de partida para o desenvolvimento de sistemas mais complexos para o enriquecimento semântico de modelos BIM.

São também descritas as fases de desenvolvimento de uma segunda interface de RV para enriquecimento semântico. Estas incluem a apresentação de uma abordagem openBIM para importar modelos BIM para um motor de jogo, preservando a informação semântica e geometria dos modelos e admitindo a possibilidade de validação através de *Information Delivery Specifications* (IDS).

Uma avaliação completa da usabilidade é também detalhada, incluindo avaliações formativas e sumativas, bem como o *feedback* recolhido através de 62 entrevistas com 31 profissionais do sector AECO. Os resultados mostram que utilizadores sem conhecimento prévio conseguiram interagir com modelos BIM, mesmo aqueles sem um profundo conhecimento da metodologia ou experiência com ferramentas autorais BIM (83,9% dos participantes). De facto, a maioria dos participantes foi capaz de gerir informação BIM de forma natural através do ambiente de RV, atingindo uma utilização próxima da esperada para um utilizador mais experiente. Além disso, a percepção de satisfação alcançada demonstra uma apreciação e consentimento generalizados pela aplicação da abordagem proposta às tarefas de gestão de instalações, mesmo entre participantes sem experiência prévia com RV e/ou BIM.

PALAVRAS-CHAVE: Building Information Modelling, Enriquecimento Semântico, Interfaces Naturais, Realidade Virtual, Realidade Aumentada, Usabilidade.

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NOTATION, SYMBOLOGY AND ACRONYMS

AECO – Architecture, Engineering, Construction and Operations

AIA – American Institute of Architects

ANN – Artificial Neural Networks

ANSI – American National Standards Institute

AR – Augmented Reality

BAUS – BIM Automated Updating of Schedules

BBS – Behaviour-Based Safety

BCF – Building Collaboration Format

BIM – Building Information Modelling

BiM – Building Interactive Modelling

BLE – Bluetooth Low Energy

BMS – BIM Management System

CAVE – Computer Assisted Virtual Environment

CE – Comité Estratégico

CNN – Convolutional Neural Network

CSCM – Construction supply chain management

CSV – Comma-separated values

CT – Comissão Técnica

CSFs – Critical Success Factors

DCE – Doctoral Congress in Engineering

DIS – Draft International Standard

DSR – Design Science Research

DT – Decision Tree

ELBigMAC – Educational Lab - Big Machine

EU – European Union

GML – Geography Markup Language

GPS – Global Positioning System

GUID – Globally Unique Identifier

HBIM – Historic Building Information Modelling

HCI – Human-Computer Interaction

HMD – Head-mounted display

HTML – HyperText Markup Language

HTTP – Hypertext Transfer Protocol

HVAC – Heating, Ventilation and Air Conditioning

H&S – Health and Safety

IAI – International Alliance for Interoperability

IBC – International Building Code

ICT – Information Communication Technologies

IDM – Information Delivery Manual

IFC – Industry Foundation Classes

IPR – Intellectual Property Rights

IS – Information Systems

ISO – International Organization for Standardization

IVE – Immersive Virtual Environment

IVR – Immersive Virtual Reality

JSON – JavaScript Object Notation

k-NN – k-Nearest Neighbour

LOD – Level of Development

LOI – Level of Model Information

LOIN – Level of Model Information Need

MEP – Mechanical, Electrical and Plumbing

MR – Mixed Reality

MRT - Mean Radiant Temperature

MVD – Model View Definition

NASA-TLX – NASA-Task Load Index

NB – Naïve Bayes

NBI – Natural BIM Interface

NUIs – Natural User Interfaces

OSM – Open Street Maps

OTTV – Overall thermal transfer value

OWL – Ontology Web Language

PCA – Principal Component Analysis

PII – Personal Indemnity Insurance

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PRISMA – Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols

PSSUQ – Post Study System Usability Questionnaire

ptBIM – Congress of Building Information Modelling

PTNB – Plan Transition Numérique dans le Bâtiment

QR – Quick Response

QUIS – Questionnaire for User Interface Satisfaction

RDF – Resource Data Framework

RFID – Radio Frequency Identification

RGB – Red, Green, and Blue

ROI – Return On Investment

SE – Semantic Enrichment

SLAM – Simultaneous Localisation and Mapping

SOA – Service-oriented Architecture

SPARQL – SPARQL Protocol and RDF Query Language

SPF – STEP Physical File

STEP – Standard for the Exchange of Product Model Data

STriDE - Semantic Trajectories in Dynamic Environments

SVM – Support Vector Machines

SUMI – Software Usability Measurement Inventory

SUS – System Usability Scale

SWRL – Semantic Web Rule Language

UIM – Urban Information Modeling

UK – United Kingdom

URI – Unique Resource Identifier

US – United States

UT1 – Users type 1

UT2 – Users type 2

USACE – United States Army Corps of Engineers

UWB – Ultra-wide-band

VIDEWS – Visualizing Intrusions in Dynamic Environments for Worker Safety

VCS – Virtual Construction Site

VR – Virtual Reality

WBS – Work-Breakdown-Structure

XML – Extensible Markup Language

1
INTRODUCTION

1.1 STRUCTURE OF THE CHAPTER

The opening chapter of the thesis initiates with an overview of technology acceptance as an overarching introductory topic to expose the scope of the study. The following sections detail the motivation to conduct the present thesis, further detailing its aim and objectives. The chapter ends with an outline of the structure of the document.

1.2 A PERSPECTIVE ON TECHNOLOGY ACCEPTANCE

The perception of something new by an individual, or a different adoption unit, underpins the notion of innovation [1]. The possibility of an innovative and correspondingly disruptive concept, such as a new technology, is seldom assisted by spontaneous adoption. Slow-paced incremental phases of acceptance frequently precede the pronouncement of a new technological paradigm. Indeed, as stated by David [2], the acceptance of a new paradigm by the industry, even as prevailing as the employment of electrification or the introduction of the computer, is usually a protracted and stepwise adaptation process despite clear potential benefits. The adoption rate relates to “the relative speed with which an innovation is adopted by members of a social system” and can be depicted in an adoption curve - *S-shaped diffusion curve* (Figure 1) - relating individuals (adopters) over a certain amount of time [1].

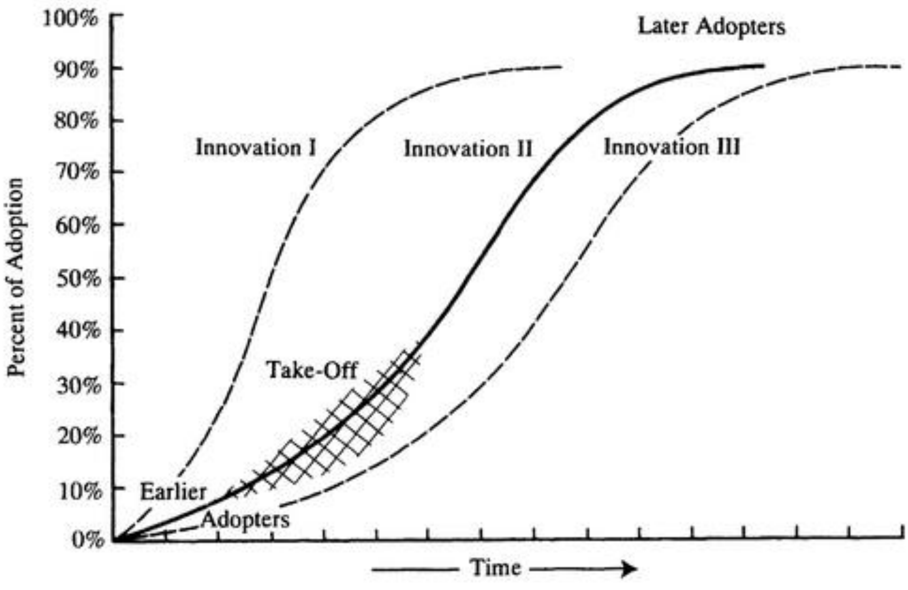

Figure 1 - S-shaped diffusion curve (cumulative), adapted from Rogers [1].

There is a recognised reluctance among the agents of the Architecture, Engineering, Construction and Operations (AECO) sector regarding the acceptance of new technologies and innovations (e.g., Building Information Modelling - BIM) [3] largely due to the fragmented nature of the industry [4]. Conversely, construction projects have become more complex and competitive [5]–[7], triggering Information Communication Technologies (ICT) development to tackle projects demanding nature [8] as well as requirements for access to information, communication, collaboration and evaluation [9] (see also [5], [10], [11]). Despite the demand for progress, the steep rate of technological development is still challenging for users to keep track of and fully exploit such developments [12].

The case of BIM is reported as a paradigm shift for the AECO sector [10], [13] in the traditional way of doing things leveraging formerly fragmented archive and drawing-based asynchronous workflows to real-time information-rich modelling and collaborative approaches [14]. Indeed, BIM uptake entails changes in access to project-related information [15], collaborative work [8] as well as visualisation, coordination, and maintenance capabilities [16]. Although research has reported recognised advantages from the application of this methodology to construction projects [14], [17], the BIM adoption rate has been realised slower than originally anticipated [8], [18], [19]. Despite public authorities and government bodies' efforts to the requirement for BIM in public procurement [20]–[22], BIM is still not entirely embraced by all segments [15]. For instance, the management of information and simultaneous systematisation of the role of the actors leveraged by the standard ISO 19650 [23] and Directive 2014/EU, in particular, Article 22 [24], present some of the international initiatives toward BIM uptake. Regardless of such initiatives to promote the methodology in public tenders, BIM requires further developments to become fully integrated and collaborative among the various stakeholders involved. Possible reasons for this effect may be related to the inertia of the AECO sector in the adoption of new working methodologies and practices, lack of awareness of the advantages and clarification of the responsibilities of each stakeholder [3], and a poor realisation of BIM prospective benefits in each stage of construction projects. Hence, the need for adaptations and more supportive technologies emerges as a way to enhance collaboration and inclusiveness amongst teams and stakeholders. Kerosuo et al. [25] report a demand for developments able to leverage BIM towards a more flexible range of technologies oriented to the people and their tasks within construction projects. Indeed, the establishment of BIM as current work practice is still hindered by several factors. To fully address this issue, two major databases were used to research recent implementation barriers and limitations of BIM adoption on a global scale. Although no longer a prominent research field from 2016 to the present date, the results suggest that cost and investment, policy and legislation concerns, acceptance and usability issues, interoperability and data handling were the most referenced causes affecting the uptake of BIM. The complete research procedure and analysis are detailed in Chapter 2.

Given that BIM tools could benefit from the development of more supportive ways that are tailored to the tasks, context, profile, and competence of the people who will use them (i.e., end-users), this thesis proposes that developing innovative interfaces for improved access to BIM information can positively contribute to the methodology/technology acceptability and adoption rate.

1.3 MOTIVATION

Considering the diversity of stakeholders in the AECO sector, not every party is guaranteed to be BIM or technology-savvy. Ponder the case of a master builder as an example who, despite intense years of experience in the AECO sector, does not possess the necessary skills to take advantage of BIM tools. This case demonstrates a scenario where the user may face additional challenges in playing an active part in a more digitised value chain, although having practical expertise. Hence, alternative approaches and techniques should be considered to provide innovative means to access, manage and enrich BIM models, thus providing more direct, usable and interoperable experiences. Such approaches may encompass the combination of immersive environments and Natural User Interfaces (NUIs) to increase the Level of Information (LOI) of BIM projects through task-driven applications, enabling more practical and attuned systems.

On another note, the digitisation of the AECO sector is faced with the absence of a full-fledged acceptance of the BIM methodology, providing the opportunity for further developments in the way of interacting, accessing and exchanging BIM data.

Favourable results from the applications of Virtual Reality (VR) and Augmented Reality (AR) have been reported within the AECO sector and related research fields provided by recent developments in VR and AR-related hardware and software, which are increasingly affordable to the average consumer. The prospective benefits of immersive technologies and NUIs pave new grounds for research, particularly in studying assessment methodologies to understand the suitability of those interfaces to the AECO sector; in the development of supportive technologies to enable the use of BIM, attending to available human resources and their requirements; as well as in promoting feasible access to BIM non-geometrical information.

This thesis motivation is based on the hypothesis that suitable immersive BIM-based interfaces may prevent the exclusion of sectors of construction project teams that might be less familiar with BIM methodology, thus presenting a contribution to the generalised use and acceptance of BIM. Furthermore, the present thesis assumes an overarching research question: "What techniques would take advantage of the traditional approaches and empirical knowledge of AECO actors in line with the technological advance of the industry?". The aim and corresponding objectives defined to answer such a question are described in the following section.

1.4 AIM AND OBJECTIVES

The main aim of the present thesis concerns the development of immersive BIM-based interfaces to provide generalised access, enrichment and maintenance of models' non-geometric information. Four intermediate objectives were defined to fulfil this main goal:

1. Definition of the theoretical basis and state-of-the-art analysis on three key topics:
   1.1. A literature review concerning the state of the art of BIM-based VR applications in the AECO sector;
   1.2. A literature review concerning the state of the art of BIM-based AR applications in the AECO sector;
   1.3. A literature review regarding Semantic Enrichment (SE) methods and applications;
2. Development of a methodology to assess the suitability of immersive BIM-based interfaces;
3. Development of BIM-based immersive interface prototypes;
4. Application of the proposed methodology to validate an immersive BIM-based interface.

After the definition of the main aim and objectives of the thesis, a detailed literature review was conducted targeting three fundamental topics: VR, AR, and SE. In particular, two systematic literature reviews were performed to ascertain the most recent methods, their impact, best practices, and assessment methods on the application of BIM-based VR and AR interfaces, respectively. Furthermore, a third systematic literature review was conducted to disclose BIM and SE developments during the last decade.

Upon the conclusion of the literature review, a thorough analysis regarding the usability of systems was performed to provide a practical methodology to be applied in the assessment of immersive BIM-based interfaces in the AECO sector. This methodology was used to validate the suitability of a proposed immersive interface for SE.

Two systems of immersive BIM-based interfaces for non-geometrical information management were achieved. While the first prototype comprised the early development stages of this thesis and was thus tested in laboratory facilities, the development of the second interface was followed by a full-fledged usability assessment methodology to assess the suitability of the proposed solution to the AECO sector.

1.5 OUTLINE OF THE THESIS STRUCTURE

The remaining document is organised into five chapters:

- The introductory chapter, chapter 1, comprises the introduction to this thesis, the motivation to conduct this study, and describes the main goal and secondary objectives.
- Chapter 2 refers to the state-of-the-art of central research topics underpinning the present thesis. This chapter presents three systematic literature reviews, among other complementary literature research. In particular, the chapter elaborates on two reviews concerning BIM-based VR and AR applications to the AECO sector and a final review on the topic of SE applications and methods, respectively. Complementary literature research focuses on topics related to NUIs, openBIM formats, data exchange, interoperability, and information requirements.
- Chapter 3 dwells on the usability of systems and assumes a more propositional quality by introducing a proposal for a methodology for the usability assessment of immersive interfaces.
- The contextualisation of NUIs and their relation to BIM is presented in chapter 4. Also, this chapter comprehensively describes the workflow and system architecture of the developed interfaces. Additionally, a thorough usability assessment is presented, focusing on the application and suitability of the second interface to support the semantic enrichment of BIM models.
- Chapter 5 presents the conclusion of the thesis and indications for future works.

2
STATE OF THE ART

2.1 STRUCTURE OF THE CHAPTER

The current chapter presents the state of the art of central research topics underpinning this thesis. It starts with a brief literature review regarding BIM implementation barriers and expands to complementary concepts and introductory notions setting forth the knowledge base of this work. Afterwards, the chapter includes three systematic literature reviews concerning VR, AR, and SE, to ascertain current research gaps and challenges on core topics to which the present work intends to contribute.

2.2 A BRIEF NOTION OF LIMITATIONS AND CHALLENGES TO BIM IMPLEMENTATION

Despite public authorities and government bodies' efforts toward BIM in public procurement [20]–[22], the adoption-rate of this methodology has been realised slower than initially anticipated [8], [18], [19]. To better grasp the existing implementation barriers and adoption limitations of BIM to a global extent, a review was conducted on two major databases (Scopus and Web of Science) using the keywords combinations: ((BIM OR “Building Information Modelling”) AND Implementation); (BIM OR “Building Information Modelling”) AND Adoption); and (BIM OR “Building Information Modelling”) AND Limitations). Only journal and review papers were considered, published from 2016 to 2019, addressing limitations and existing barriers to the uptake of BIM on a global approach. Examples such as national case studies comprising sector constraints and local industry limitations were not considered. Only articles targeting an international and holistic overview were chosen for further analysis. Table 1 summarises and groups the limitations found after screening the selected papers.

Table 1 - BIM main implementation barriers.

Subjects	Limitations and challenges to BIM implementation	Reference
Cost and Investment	Significant investment in training, formation, as well as software and hardware requirements.	[21], [26], [27]
	High technology cost and Return On Investment (ROI) concerns.	[21]
Policy and Legislation Concerns	Uncertainty regarding the ownership and authorship of collaborative models.	[21], [8]
	Lack of BIM contract-related aspects and details.	[18]
	Intellectual Property Rights (IPR) and copyright concerns.	[18], [8]
	BIM legal concerns (e.g. collaborative framework, Personal Indemnity Insurance (PII)).	[18]
	Lack of support to policymakers in developing implementation strategies.	[28]
	Lack of guidelines for policy development (macro level).	[28]
Acceptance and Usability	Resistance to implementing new work practices and procedures.	[18], [29]
	Lack of trust, motivation, understanding and difference in skills towards BIM.	[18], [8]
	Non-user-friendliness.	[21]
	Steep learning curve.	[29]
Interoperability and Data Handling	Interoperability limitations.	[8], [18], [21]
	Data handling and storage issues.	[18]
	Lack of instruments to share, track, and verify data as well as control versions.	[18]
Market demand	Lack of demand.	[21]
	“The lack of benchmarks to assess and comparing whole markets”.	[28]
Other issues	Lack of understanding regarding workflows and processes.	[29]

Although few studies were found targeting a worldwide overview of BIM adoption barriers, most screened papers describe “policy and legislation concerns” and “acceptance and usability” issues as the leading causes for the slow uptake. It was also verified that interoperability is still an impairing factor parallel to the inactivity of the market demand for BIM, as well as cost and investment difficulties. The found limitations are aligned with previous reviews on BIM’s Critical Success Factors (CSFs) (see also Ozorhon and Karahan [30]).

More efforts are necessary to address the main barriers hampering BIM take-up that still lacks proper adaptation to different tasks and operations [3], [15], [25], thus not becoming a fully collaborative methodology. In this regard, previous research had already paved the way toward developing BIM-based interfaces adapted to different user profiles [31]–[33].

The following sections elaborate on interoperability, data handling, technology acceptance, and usability-related topics.

2.3 On the exchange of BIM data

The multidisciplinary and scattered nature of the AECO sector and its projects [15] provides added complexity to the interaction between information maintenance systems (see also Laudon and Laudon [34]). Indeed, construction projects embrace various teams and project stakeholders (e.g., Managers, Technicians, Operational staff, and Clients/End-users) where BIM information is exchanged within different phases (i.e., Design (i), Construction (ii) and Operations & Maintenance (iii) – Figure 2).

As part of the information systems and data maintenance technology for construction projects, BIM holds specific roles among different usage interfaces [20]. As such, Figure 2 presents the agents of a construction project and the corresponding interfaces where BIM might play different usages in accordance with Kerosuo et al. [25]. Additionally, a larger grey sector pertaining to Technicians was added to depict their recent modelling role, carried out by draughtsmen in the not-so-distant past. This image is devised from an adaptation of Dinis et al. [35], originally based on Laudon and Laudon [34] and Poças Martins [36].

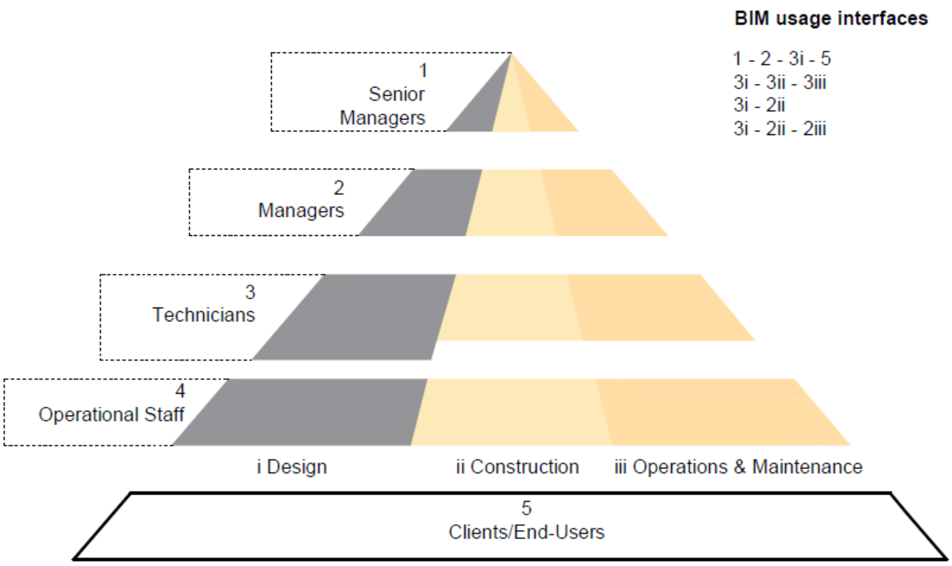

Figure 2 - Agents, their interactions and BIM usages within the interfaces of construction projects, based on [34]–[36].

Well-trained AECO professionals are necessary to take advantage of the full potential of BIM processes, although these usually assume a relatively narrow position in the pyramid – Technicians (3). Full BIM-based collaboration between stakeholders, workers and team members is still scarce; therefore, adaptative and supportive technological developments should address this identified gap [25].

In this study, the term “permeability” of BIM is used, in preference to diffusion or even adoption, to define the bidirectional interchange of BIM information amongst the agents portrayed in the different levels of the pyramid (Figure 2). As such, the permeability of BIM relates more to the idea of transposal, a theoretical crossing over hierarchical barriers, expertise and knowledge within teams. Terms such as implementation and adoption could lead to a broader sense of BIM acceptance by an entity or even sway the understanding in the sense of multi-organisational diffusion. Permeability is closely related to Figure 2 and the notion of different interfaces where BIM plays individual roles. Furthermore, permeability relates to the idea of deployment and propagation that building information must attain across work hierarchy levels (suited to the tasks and context).

This study argues that innovative interfaces such as those based on VR and AR technology may play a favourable role in improving the “permeability” of BIM.

2.4 INTEGRATED PROJECTS

The AECO sector is recognised as a multidisciplinary field where several stakeholders are actively involved in project development [15]. The complexity of construction works, and the sheer number of teams and disciplines from design to operation substantiates the paramount requirement for effective communication and integration strategies. Backman [37] alludes to the fact that the design and subsequent realisation of a building rely on constant critical input from the various disciplines resulting in a network of decisions supported by information. However, the diversity of today’s demands relies on a series of often not communicating systems. The articulation of information and the communication of data between teams and stakeholders is key to a more effective response. Integration as a work methodology for the disciplinary articulation between the actors in the development of the project and the construction process should embrace all parties involved, from the designers, the owner (or representative), managers, and the future end-users and trade crews - an “integrated vision of the building by all the specialties, the Integrated Project” [38].

According to the provisions for implementing integrated projects in the Sixth Framework Programme of the European Union [39], integrated projects “comprise a coherent set of component parts, often in the form of sub-projects implemented in close coordination, which may vary in size and structure according to the tasks to be carried out, each dealing with different aspects of the overall project implementation plan needed to achieve its agreed objectives”. This document stresses the relevance of integrated projects and details their integration in a set of forms: Vertical Integration (principal stakeholders, including users); Horizontal Integration (regarding multidisciplinary activities); Activity Integration (inclusion of research activities); Sectorial Integration (private and public sector, particularly between academia and industry); and Financial Integration (public and private funding).

The vision of an integrated project assumes noteworthy significance to this thesis through the clear objective of allowing more AECO actors to access the tools and information used in BIM projects. As such, optimising decisions and exchanging multidisciplinary insights and information as part of an integrated delivery approach are key aspects to be considered in the scope of the solutions proposed by the present work.

Exchanging information through various means, such as dialogue and direct or digital transfer, often leads to error-prone situations. Similarly to other relevant industry segments, the AECO sector is faced with more competitive and complex projects [6], [7] with continuously shorter budgets and due dates, highly demanding quality assurance and monitoring needs resulting in added costs and pressures. Additionally, AECO is recognised for its low productivity [22], which leads to digitalisation as a way for the sector to pursue more performance and accuracy among the processes, minimising costs and streamlining production. In this regard, the implementation of BIM as a paradigmatic shift for the industry [10], [13] entails inevitable clashes with more traditional and sectorial-embedded approaches. Indeed, trade crews and many industry stakeholders still lack the knowledge to take full advantage of BIM potential, for instance, during the operations phase [25] or in real-time communication amongst project teams [40]. Therefore, complementary approaches are deemed necessary to simultaneously improve BIM uptake and foster the inclusion of all parties involved in construction project teams.

2.5 INNOVATIVE INTERFACES APPLIED TO THE AECO SECTOR

Research has shown that human-computer interactions may be improved through alternative approaches, such as the implementation of immersive applications [41]–[49]. Indeed, immersive systems have been introduced to the AECO sector during the last few years, causing a profusion of case studies that draw new paradigms for the industry and involved research fields.

The entertainment industry has driven hardware prices to become more convenient to the masses, thus increasing its acceptance [50], which was matched by the steep development of technology in fields such as computer science and computer graphics. As a prime example, VR and AR technology, in times highly processing-power-demanding and expensive equipment, are now increasingly more affordable [51]. These technologies have achieved relevant developments during the last decade in low-weight and affordable equipment (e.g., head-mounted displays (HMDs)), followed by improved game engine functionalities that ease the effort needed to develop immersive applications. Game engines' growing compatibility with asset packages (i.e., OpenVR [52], Vuforia [53], ARKit [54] or ARCore [55], Photon Unity Network [56], among many others) allows streamlining the development of VR and AR interfaces.

2.5.1 Natural User Interfaces

NUIs may be defined as a range of processes and/or devices that enable a performance level similar to that of an experienced user, although requiring the least effort and time to achieve it [57]. NUIs allow for the sense of almost instant expertise based on the use of already acquired skills and by lowering the users' cognitive load [58]. The interactions are intended to be as direct to the users as to the point that they seem natural.

Motion and gesture tracking devices (e.g., Project Kinect for Azure [59], Leap Motion [60]), pen-based, touch and multitouch detection on handheld devices, and voice recognition (e.g., Microsoft's Cortana [61], Apple's Siri [62]) comprise the myriad of solutions encompassed by NUIs [63].

Taking into consideration the end-users context and needs to which the interfaces are developed is paramount to achieving a natural interaction and experience. Wigdor and Wixon [57] refer that some of the fundamental aspects of NUIs, more than technology inputs and outputs, are the experiences provided, the actual adjustment to the users' demands, tasks and context of use. Furthermore, the term natural is profoundly related to the notion that a user's behaviour must resemble as “a natural” when using the interface.

Even within the scope of AECO, known from its stakeholders' resistance to uptake disruptive technologies, research on NUIs may pave new ways to democratise practice and access to technology, attending to the variety of user profiles, knowledge background, and worksite conditions. Furthermore, considering the context found on most construction sites, it may be anticipated that the (otherwise) expected convenience of voice recognition features or touch commands may not always suit the users' working requirements, skill level, or needs. Indeed, construction sites are complex, noisy and hazardous environments where voice commands might not be fully appropriate. Another aspect that should be considered is that using flat, touch interfaces may become an unpleasant experience when dealing with busy environments exposed to dirt and weather. The alternative for HMD-based interfaces, combined with gesture-tracking interactions, could be considered as the technology may release users from the burden of holding a device and paying an unreasonable amount of attention towards interacting with a new system.

In the following sections, two key technologies will be discussed that may be applied to the development of NUIs.

2.5.2 Introduction to Virtual Reality

An unavoidable concept when addressing the subject of immersive interfaces is that of the virtual continuum introduced by Milgram et al. [64] when seeking clarification on the relationship between

AR and VR. According to the authors, the continuum is presented to illustrate the idea that AR can be described "in terms of a continuum relating purely virtual environments to purely real environments" [64]. Also, the authors contend that the realisation of the technologies (i.e., VR and AR) should be regarded more as a continuum rather than direct opposites, therefore included in a "Reality-Virtuality (RV) continuum" [64], depicted in Figure 3. The authors also allude to the generic concept of a Mixed Reality (MR) environment as one resulting from the combination of virtual and real objects.

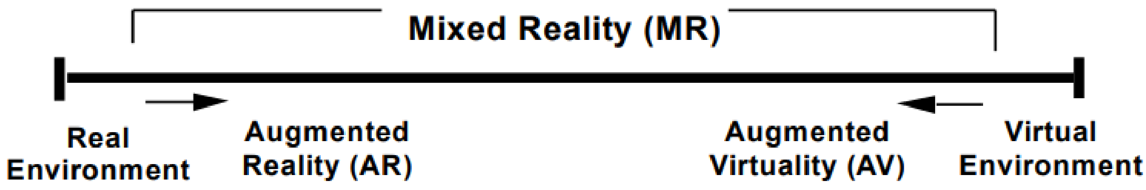

Figure 3 – Reality-Virtuality continuum, adapted from [64].

According to Martín-Gutiérrez et al. [51], VR may be defined as a computer-based simulated reality that comprises the use of specific software and hardware to provide a realistic immersive experience. Bamodu and Ye [65] describe a three-type classification attending to the immersion of the VR system and its features: immersive, semi-immersive, and non-immersive.

Immersive VR environment features allow users to feel part of the virtual scene providing the highest level of immersion. These systems usually include the use of HMDs and tracking technology, as illustrated in Figure 4.

Figure 4 – Example of an HMD with complementary controllers and tracking system, adapted from [66].

The notion of Immersive Virtual Environments (IVE) comprises a broader concept encompassing some of these systems, namely those with a higher level of immersion. Bailenson et al. [67] describe IVEs as virtual environments capable of improving users' sense of presence, tracking their movements such as head orientation and body position and returning an answer from the virtual environment.

Despite recent interest in VR propelled by computer power improvements and consequential price reduction, VR is far from an early technological breakthrough. Indeed, Morton Heilig prototyped one of the first VR initiatives, Sensorama, in 1962 (Figure 5). The device consisted of a 3D video simulator with features such as body tilting, scent and wind.

Figure 5 - Sensorama simulator, adapted from [68].

Although HMDs are more commonly associated with VR, former AR initiatives based on HMDs date back to 1965 by Ivan Sutherland. Targeting AR, Sutherland's forerunner Ultimate Display – Sword of Damocles, "a room within which the computer can control the existence of matter" [69] (Figure 6), was a reportedly heavy mechanical arm suspended from the laboratory ceiling, able to track the user's movement and display an image accordingly [70]. This device put forth the first endeavours of the development of HMDs.

Figure 6 - One of the first initiatives of an HMD - The Sword of Damocles, adapted from [71].

CAVE-like (Computer Assisted Virtual Environment) setups are part of the semi-immersive type. These interfaces combine a high level of immersion based on projections. As illustrated in Figure 7, the CAVE consists of a semi-immersive virtual setting and was initially presented at SIGGRAPH 92'[72].

The system distinguished itself by providing a means of collaborative visualisation, improved field of view and high resolution [72].

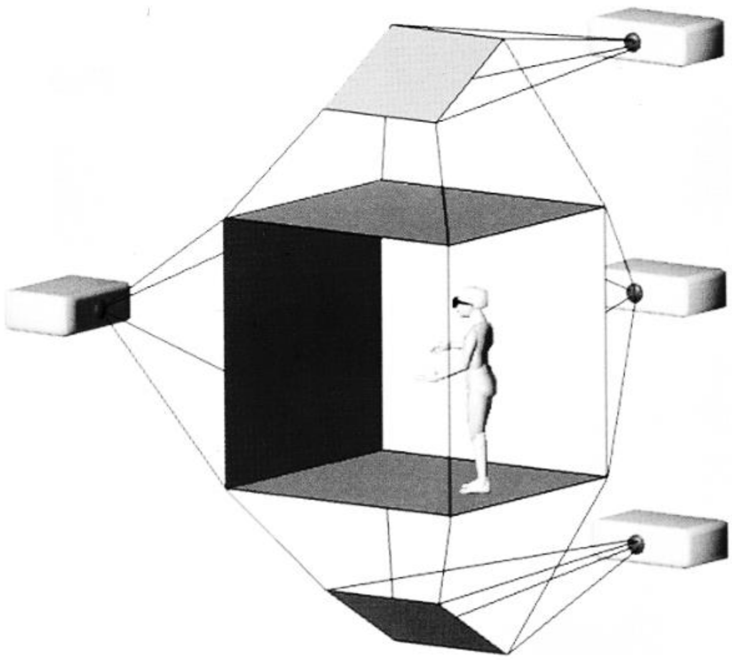

Figure 7 - The CAVE system, adapted from [72].

Finally, non-immersive systems, also known as desktop VR, rely on screens to convey the visualisation, representing a more traditional approach to VR.

Although usually associated with the entertainment industry, VR technology applications are reported in a comprehensive range of research fields such as medicine [70], nutrition and public health [73], manufacturing [74], aviation industry [75], participation in the design process [76], acoustic comfort [77], architectural heritage [78], engineering education [42], among several others.

2.5.3 Virtual Reality in the AECO sector

VR research has sought to pave the way for new approaches affecting the whole life-cycle of construction projects and displaying favourable results in construction design [79], [80], [89], [81]–[88], collaboration amongst stakeholders [79]–[81], [84], [90], [91], management [92]–[95], construction safety [49], [96]–[100] as well as engineering education [42], [50], [108]–[110], [100]–[107].

A study by Heydarian et al. [85] compares the performance of regular office tasks completed in physical environments with the same tasks performed within an immersive scene using an HMD. The authors ascertain that there were no substantial differences between the two methods, thus confirming the potential of IVEs to attain feedback from the end-user as well as to improve design tasks.

The improvement of design and review tasks was also researched by Du et al. [80], who developed a virtual scenario where multiple users may connect to an IVE using HMDs.

Regarding collaboration, a method was developed by Du et al. [111] to enable multiple users to perform automatic design changes from a virtual scenario to update the underlying BIM model. On a similar topic, Dinis and Poças Martins [112] developed a framework to allow users, with and without previous experience in the AECO field and VR, to interact with the geometric information of a BIM model using an HMD and a motion-tracking device. The modifications made to geometry within the IVE are automatically updated in the corresponding BIM model.

Multiuser VR trials are suitable to be performed in semi-immersive interfaces such as CAVE-like setups. For instance, the design and review of medical facilities have been supported by setting up a CAVE system [45], [71] in which multiple users may stand in the same location and experience an immersive environment (Figure 8). Such applications convey enhanced spatial perception to participants who do not hold construction or architectural expertise, although they may use the facilities in the future.

Figure 8 - Design and review of medical facilities through the support of CAVE setups, adapted from [45], [71].

Majumdar, Fischer and Schwegler [87] report the use of a CAVE setting over a more traditional approach (i.e., plywood mock-up models) to review the design of a courtroom. Some of the benefits stressed are more efficient means of communication, improved collective attention and the rapid resolution of issues.

Concerning facility management, Yang and Kensek [95] describe an approach to integrate and overlay BIM data attributes (i.e., object name, cost and manufacturer) on top of the corresponding objects in immersive VR.

To reach a controlled event for testing, Sacks, Gurevich, and Belaciano [93] devised a hybrid virtual construction site (VCS). The virtual environment allowed the authors to analyse trade crews' decision-making processes and behaviours regarding managing work and production. Additionally, the authors report cost-efficiency over the laborious working hours that would have to be spent to conduct the same tests on-site and the ability to proceed with quick replications and comparisons.

Regarding construction safety, Sacks, Perlman, and Barak [99] conducted a series of comparison tests between conventional safety training methods and immersive VR approaches (i.e., CAVE-based setting, power wall). The authors assert that the immersive VR interface was more effective than traditional learning experiences for specific tasks such as stone cladding and cast-in-situ concrete work. Furthermore, the authors highlight that VR enables the simulation of hazardous situations without endangering or compromising safety. Also, the VR safety training showed positive results in maintaining the participants’ levels of attention.

Messner et al. [110] applied a CAVE-like projection system technology in an undergraduate Architectural Engineering programme. The authors suggest that the display can be beneficial to improve the understanding of planning issues, often constrained by the students’ present knowledge and limited visualisation expertise to recognise issues concerning planning in construction design.

The plethora of applications exploiting the potential of VR in the AECO sector reflects a diversity of hardware and software being used. Another aspect worthy of attention is that only part of the systems takes full advantage of BIM models to develop virtual environments. Hence, the present work focuses on specific types of immersive VR systems based on BIM models and herein defined as BIM-based VR interfaces. This system exploits the geometric accuracy and the non-geometric data contained in BIM models to develop virtual scenarios. Additionally, BIM-based virtual interfaces are usually backed by game engines which, according to Natephra et al. [82], can improve the potential of BIM.

The following section presents a systematic review conducted to ascertain the impact, best practices, and current knowledge on the application of BIM-based VR in the AECO sector.

2.5.4 BIM-based VR systematic literature review

The systematic review was developed based on the protocol of Sidani et al.[113] (PROSPERO Register Number: CRD42018085845), stating the use of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [114]. Also, a few relevant revisions were performed to this protocol regarding the inclusion criteria. After the first screening (i.e., exclusion criteria), the remaining articles were examined to exclude papers non-related to BIM-based VR interfaces, manuscripts that did not provide user tests or assessments of their tools, and those that did not use immersive VR technologies. Also, research questions were aligned to better address the scope of the review (Table 2).

Table 2 - Research questions.

Q1	What is the purpose of VR implementation in construction projects?
Q2	What is the main framework and system architecture being used?
Q3	Why are applied interfaces and the respective tools selected?
Q4	At which stage of the project’s lifecycle is VR being implemented?
Q5	How are these interfaces being assessed?
Q6	What are the main target groups?
Q7	What are the main limitations?
Q8	Were the limitations solved by later studies?
Q9	How is BIM related to VR?
Q10	What are the mainly researched BIM dimensions?
Q11	Is BIM achieving its full potential with VR?

The research was performed using a set of electronic databases rendered in Table 3.

Table 3 - Queried databases.

Database type	Category	Included Databases
Index	Multidisciplinary	Academic Search Complete Current Contents Web of Science SCOPUS
	Engineering	INSPEC ScienceDirect
E-Journal	Multidisciplinary	Cambridge Journals Online Directory of Open Access Journals Emerald Fulltext Informaworld (Taylor and Francis Online) Oxford Journals SAGE Journals Online Scientific Electronic Library Online (SciELO) SpringerLink Wiley Online Library
	Engineering	ACM Digital Library ASME Digital Collection CE Database (ASCE) IEEE Xplore IOP Journals ScienceDirect (ejournals) SIAM

An initial set of 2950 articles was collected from the keywords provided in the protocol. Afterwards, exclusion criteria were used to reduce the number of remaining papers (Table 4). In detail, the application of the exclusion criteria further reduced the initial number of 2950 to 75 papers by excluding articles released prior to 2007 (748); non-journal articles (957); not related subject areas (375); non-English articles (18); off-topic articles (464); and articles manually identified as duplicates (313).

Table 4 - Exclusion criteria and the corresponding number of articles excluded.

Exclusion Criteria	Number of articles excluded
Articles released prior to 2007	748
Non-journal articles	957
Not related subject areas	375
Non-English articles	18
Off-topic articles	464
Articles manually identified as duplicates	313
Total number of articles excluded	**2875**
Remaining articles	**75**

Of the remaining 75 articles, seven lacked the availability of the full text, while all the others were read to their full extent. Among the remaining 68 documents, 56 were deemed out of scope, including 33 that did not describe the use of immersive VR systems. The remaining 12 papers and two initial records identified through other sources (i.e., snowballing) were thoroughly analysed. A final search was performed on the references of the articles that achieved the inclusion criteria (snowballing), eliciting two other relevant papers. Hence, 16 research papers were thoroughly analysed and included in the final review. Figure 9 illustrates an overview of the research process.

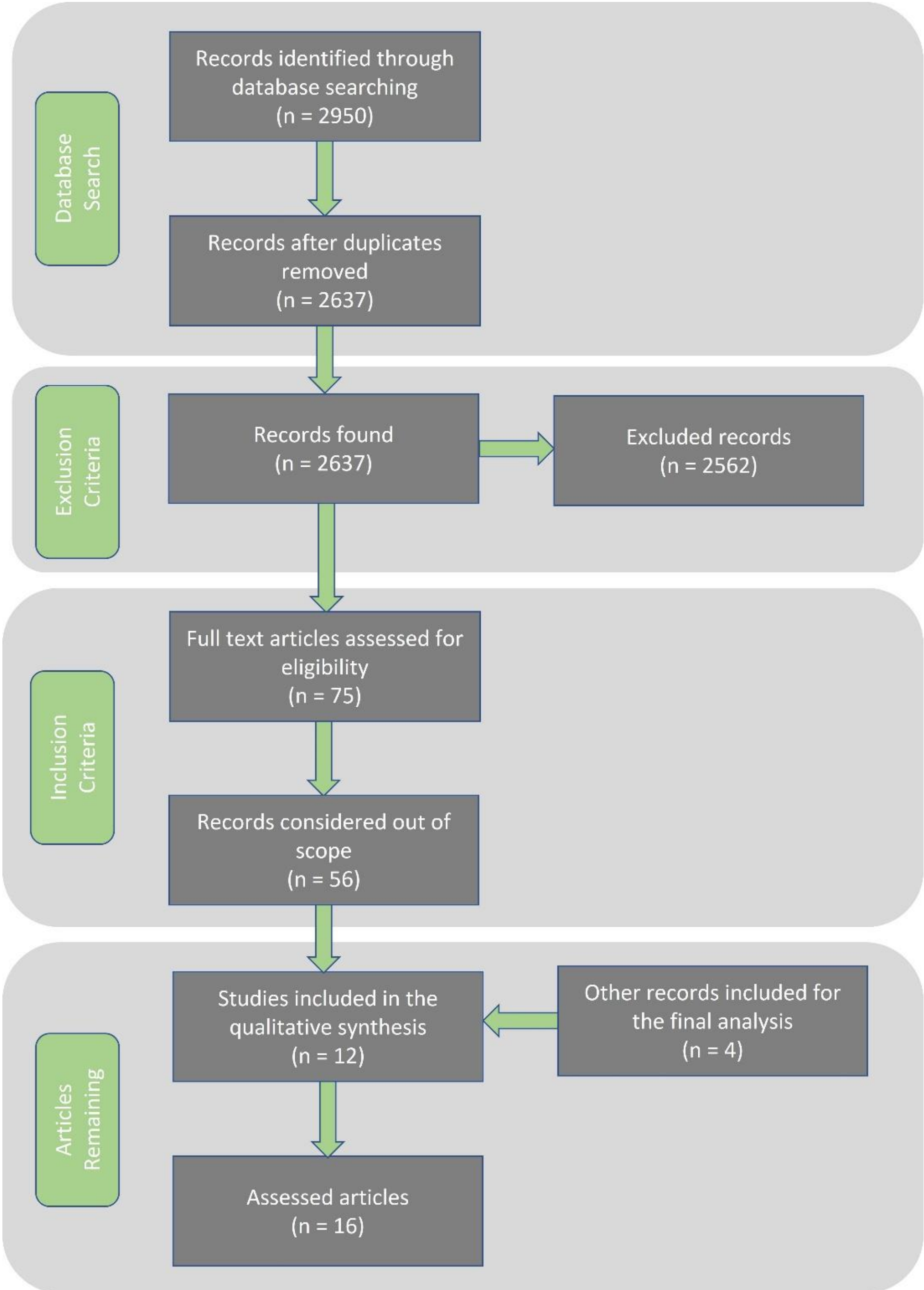

Figure 9 - Strategy for selecting relevant articles for the BIM-based VR systematic literature review, adapted from [115].

The remaining 16 articles were analysed to classify the most contributing authors, identify frequent journal publications and organise their respective fields within the Construction industry.

The papers were released from 2013 to 2018, with over half published between 2017 and 2018. At the time of writing, an average of 85.87 citations per article was verified, with four papers distinguishing themselves with over 100 citations: Boton [90] (122 citations);), Du et al. [80] (130 citations); Wang et al. [49] (146 citations); and Hilfert and König [83] (228 citations).

Sacks authored three of the 16 publications [92], [93], [97], 2 of them in collaboration with Gurevich. Among the most contributing authors, Wang collaborated twice with Li [49], [84]. Du, Shi and Zhao authored two publications [80], [91].

Concerning the article sources, three small clusters were identified. Displaying two contributions each, Automation in Construction and Procedia Engineering; Visualization in Engineering produced three of the 16 articles. Additionally, the screened publications were grouped into 6 research fields, afterwards divided into primary and secondary according to their relevance in each publication (Table 5).

Table 5 - Research field and the respective number of occurrences, adapted from [115].

Research field	**Total Number of Occurrences**	**Primary/Secondary Occurrences**
Collaboration – field focused on teamwork, mainly communication and cross-team interaction improvement	7	3/4
Construction Design – field focussed on improving the design stage of a construction project	6	5/1
Construction Management – field focussed on improving the management of a construction project throughout the design and construction stages	6	3/3
Construction Safety – field focussed on improving the construction site safety, mainly through increased awareness and design simulation	4	4/0
Education – field focussed on improving the knowledge of any construction-related entity (e.g., workers, engineers, architects) and/or students	5	4/1
Facility Management – field focussed on improving the management of a facility during its operation stage.	1	1/0

One of the main features of VR is the potential to improve the interaction between remotely located users [80], and as expected, collaboration was the most occurring field. Boton [90], Du et al. [80], and Shi et al. [91] developed VR BIM-based applications to provide network communication between remote users.

Construction design registered six occurrences, the same as Construction Management. Related to Construction Design, Lin et al. [79] developed a semi-immersive virtual environment to allow medical teams to participate in the design process of a hospital. The authors determined that non-construction experts can easily offer valuable input to the design team, which was enabled by the system. Also, the VR environment provided communication efficiency between the design team and the healthcare stakeholders, thus improving the decision-making process.

As for the Construction Management field, Gurevich and Sacks [92] used a BIM-based VR prototype production system, "KanBIM", to assist teams in managing their working activities and achieving a better-quality workflow. Results show that the use of the VR system was effective and clear to most participants. Furthermore, the proposed system improved the reliability and accuracy of the experimental outcomes, simultaneously reducing the time needed to perform an experiment once the VR system was completed. Indeed, the effort required to create and implement the VR experiments was identified as a limitation when considering the use of VR trials in lieu of field trials.

Five occurrences were confirmed pertaining to Education, while four publications focused on Construction safety. Related to the first, Jensen [102] researched the effect of VR environments and gaming principals towards facilitating the learning process and improving the students' involvement in problem-based learning conditions. As to the second research field, Construction Safety, Azhar [96] suggests the use of BIM and VR tools to improve the visualisation of possible hazard situations, therefore providing training to engineers, architects and construction workers before the actual construction work.

Only one occurrence was specifically related to Facility Management. Shi et al. [91] describe the potential of a virtual environment to deliver remote communication between users and the facility manager. The system functionalities allowed the identification of issues regarding the Mechanical, Electrical and Plumbing (MEP) objects, hence improving the efficiency of communication in facility management as well as encouraging the project participants to achieve sustainable goals.

Analysis of the construction stages

The focus of each publication in a particular construction stage was verified, where most articles had a major emphasis on the Design stage (12 out of the 16 articles). Additionally, four publications among these focused on Pre-Construction and/or Construction stages. Overall, a total of seven papers targeted these two stages.

There were only three publications related to the Operation and Management stage. Table 6 provides an overview of the distribution of the construction stages per each screened publication.

Analysis of the target groups

In compliance with the construction stages, four target groups were acknowledged as the most occurring: engineers (nine), architects (seven), workers (seven), and owners (five). The remaining groups (i.e., building users (three), students (three), and facility managers (two)) were recognised in three or fewer articles. The distribution is presented in Table 6.

Table 6 - Construction stages and target groups identified among the screened publications, adapted from [115].

Authors	**Construction Stage**	**Target Group**
Lin et al. [79]	Design	Owners Architects Engineers
Boton [90]	Design Pre-construction Construction	Owners Architects Engineers Workers
Wang, Li and Kho [101]	Design	Engineers Students
Du et al. [80]	Design Pre-construction Construction Operation and management	Owners Architects Engineers Workers Facility managers
Cárcamo et al.[81]	Design	Owners Architects Engineers
Jensen [102]	Design	Students
Azhar [96]	Pre-construction Construction	Engineers Workers
Wu et al. [48]	Design	Students
Natephra et al. [82]	Design	Owner Architects Engineers
Shi et al. [91]	Operation and management	Facility managers Building Users
Hilfert and König [83]	Design Construction	Architects Engineers Workers
Edwards, Li and Wang [84]	Design	Building Users
Sacks et al. [97]	Design Construction	Architects Engineers Workers
Gurevich and Sacks [92]	Construction	Workers
Wang et al. [49]	Design Operation and management	Building Users
Sacks, Gurevich and Belaciano [93]	Construction	Workers

Analysis of the use of BIM dimensions

BIM authoring tools may provide accurate geometric information (3D), which is exported to game engines towards the development of virtual environments. However, exporting the geometry of a building represents only one of a much broader set of information types. Indeed, addressing the term dimension in BIM denotes the underlying data that can be accessed.

"BIM dimensions" is a rather well-established concept [116]. The dimensions can be thought of as categories, and each category has a purpose, a set of information available to the user if the building information model provides the conditions [117]. One relevant aspect that should be mentioned is the existing discussion regarding the definition of 6D and 7D. Nevertheless, this study adopts the BIM dimensions suggested by Smith [116]: 3D – Shape; 4D – Scheduling; 5D – Estimating; 6D – Facility Management Applications, and 7D – Sustainability. Additionally, BIM dimensions overlap largely with the widely adopted concept of "BIM Uses" [118].

Table 7 details the identified BIM dimensions, while the frequency of occurrence is depicted in Figure 10.

Table 7 - BIM dimensions identified, adapted from [115].

Authors	**BIM Dimensions**
Lin et al. [79]	3D
Boton [90]	3D, 4D
Wang, Li and Kho [101]	3D, 5D, 7D
Du et al. [80]	3D, 4D, 5D, 6D, 7D
Cárcamo et al. [81]	3D
Jensen [102]	3D
Azhar [96]	3D, 4D
Wu et al. [48]	3D
Natephra et al. [82]	3D, 5D
Shi et al. [91]	3D, 6D
Hilfert and König [83]	3D, 4D
Edwards, Li, and Wang.[84]	3D
Sacks et al. [97]	3D, 4D
Gurevich and Sacks [92]	3D, 4D
Wang et al. [49]	3D, 4D, 6D
Sacks et al.[93]	3D, 4D

Figure 10 presents the manifested lessening number of articles that capitalise on the use of 5D to 7D dimensions (three or fewer occurrences). Although the third dimension was identified in all articles, which comprises the building geometry, there is still an apparent gap concerning the usage of higher dimensions.

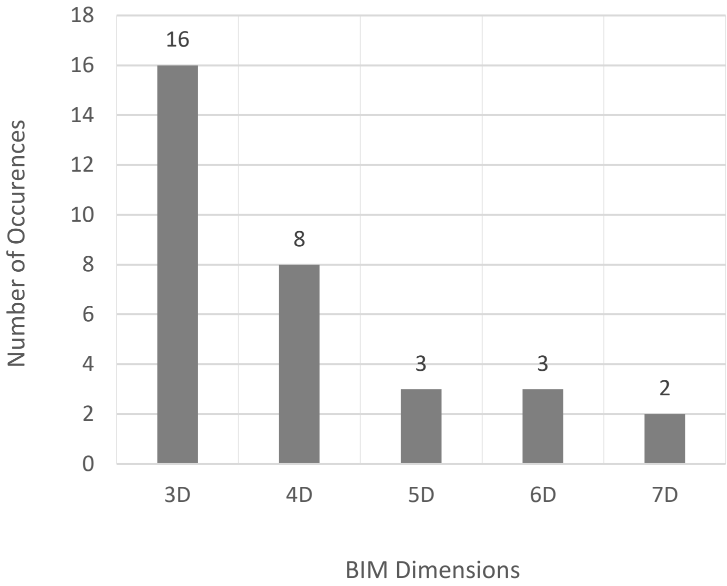

Figure 10 - Number of occurrences regarding the usage of BIM dimensions, adapted from [115].

System architecture

Detailed analysis of the architecture of the VR systems has revealed that most applications have a similar layer organisation. It has been identified that most systems are composed of three to four layers to produce a BIM-based immersive environment. The function of each layer is distinctive:

(i) BIM Model – enables accurate building geometry to be modelled and exported;
(ii) Visual Environment Enhancement – an intermediate module to provide library compatibility between game engines and BIM authoring tools, as well as model optimisation and aesthetic improvements;
(iii) Game engine – allows for the development of an immersive and interactive scenario;
(iv) Database – enables information exchange (mostly non-geometric metadata) between the BIM model and the VR environment.

An overview of the most commonly used system architecture is displayed in Figure 11.

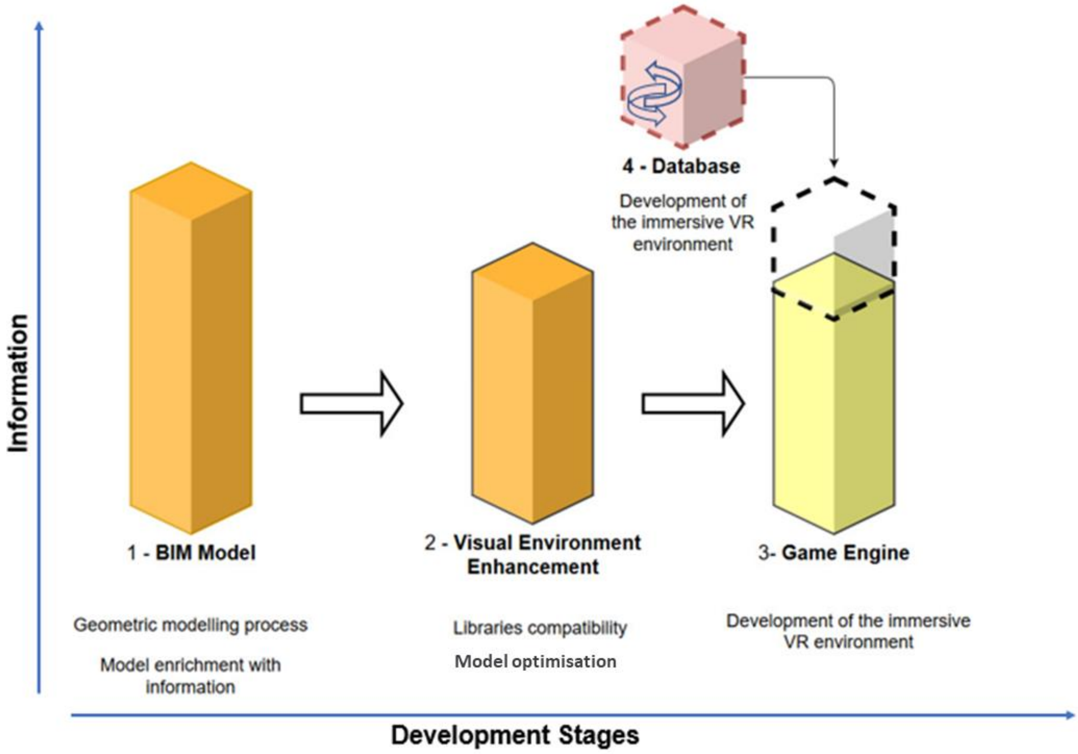

Figure 11 - Schematic representation of the most commonly used system architecture in BIM-based VR applications, adapted from [115].

Regarding the first layer, the BIM model, most authors rely on Autodesk Revit as the main BIM authoring tool for its recognised consistency with BIM standards and third-party support [84]. Thirteen out of the 16 papers used Autodesk Revit, which validates the potential of the relationship between BIM authoring tools and VR [82]. However, to overcome interoperability limitations between the exported BIM model (layer 1) and most game engines (layer 3), 3Ds Max was the generally used solution [80], [91] in “Visual Environment Enhancement” (layer 2).

Regarding the third layer, the Unity game engine holds an active support community, allows platform compatibility [81], and provides a flexible stage for the BIM model to be used within virtual scenarios. Therefore, most authors widely relied on this solution when developing a VR environment. Jensen [102] expresses that Unity enables a steady transfer of the building model from the BIM authoring tool Autodesk Revit. Nevertheless, Unreal’s rendering features regarding the interaction of light with materials were emphasised by Natephra et al. [82].

A fourth layer, “Database", was noticed among some interfaces. From this layer, users may access parametric information as well as generate automatic updates through the interactions made within the VR scene to the underlying BIM models [79], [80], [96].

One feature worth mentioning is the network connectivity component verified in some applications [80], [81] that allows for remote multiuser interaction within the same VR system.

Employed software and hardware

By identifying a common system architecture, it was possible to register the most used software solutions (Figure 12). The data suggests that most systems rely on Autodesk Revit, 3ds Max and Unity as the central software tools.

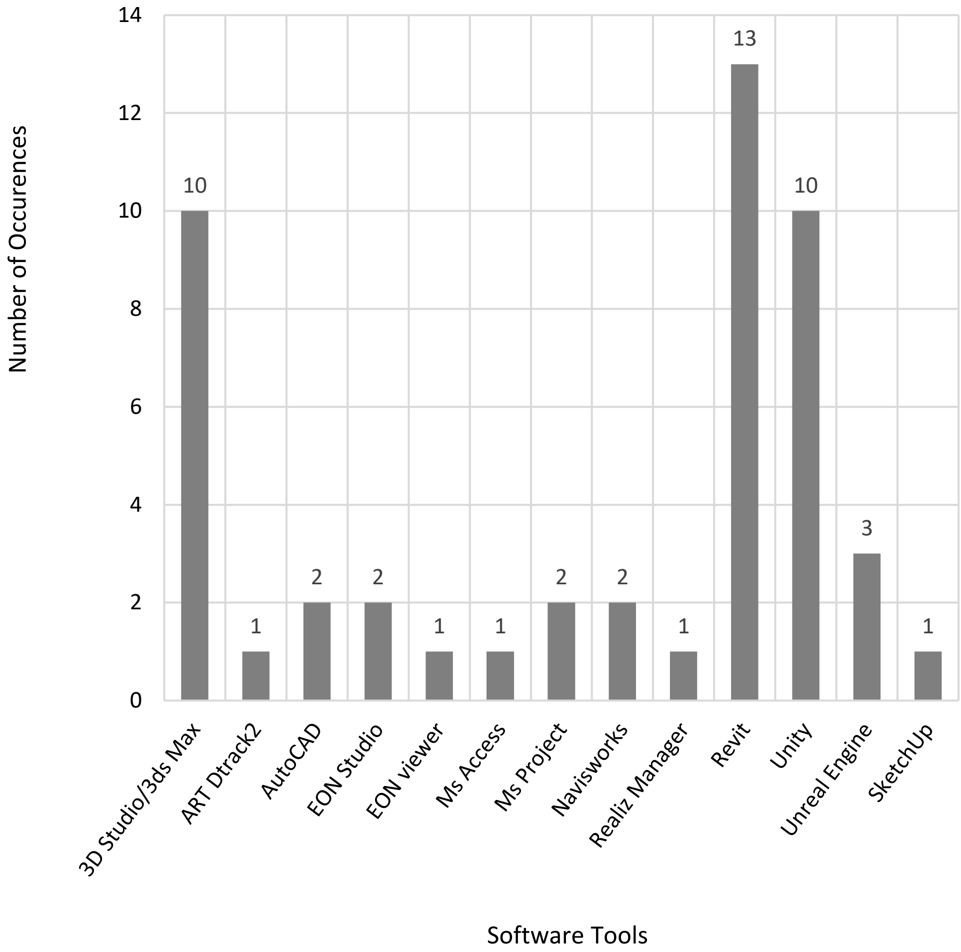

Figure 12 - Number of occurrences of the core software solutions, adapted from [115].

Concerning the most widely used hardware solutions, it was verified that most authors preferred Oculus Rift. Indeed, the possibility of realistically displaying a construction environment otherwise not possible through more traditional approaches [69], as well as being a commonly known and affordable tool [83], makes Oculus Rift a favoured solution. CAVE-based settings were the second most used display means.

Most studies verified the traditional keyboard and mouse approach as the preferred means of interaction within the virtual environment, followed by other less occurred devices such as joysticks or the motion-tracking Kinect system. Figure 13 presents the number of occurrences of the authors' preferences.

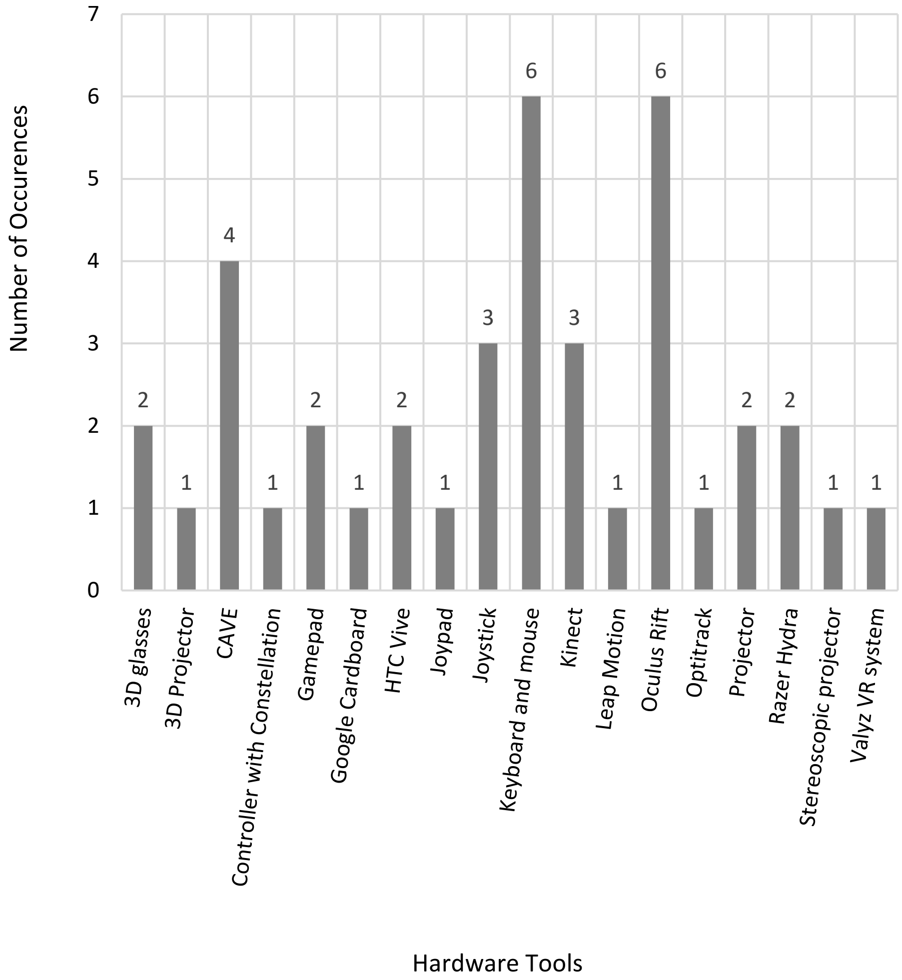

Figure 13 - Number of occurrences of the most used hardware tools, adapted from [115].

Evaluation and assessment

Regarding the assessment of the systems, it was found that 12 papers state the use of case studies to assess and validate the proposed BIM-based interfaces. Moreover, pilot tests were verified in three of the 12 case studies, while at least six studies supported their assessment using questionnaires.

Verified limitations

A major concern was identified among the screened articles regarding interoperability and software compatibility issues. Edwards et al. [84] suggest using Industry Foundation Classes (IFC) files to simultaneously transfer the 3D geometry and parametric information to the VR environment. Additionally, Wang et al. [49] emphasise using IFC instead of Revit's API to manage the data component. Shi et al. [91] describe difficulties in transferring BIM information to the game engine, while Natephra et al. [82] allude that material and texture properties could not be imported into the game engine; only the 3D geometry was successfully transferred.

Other mentioned limitations included the cost of both software and hardware, the time spent preparing the BIM model [79], high implementation costs, and the lack of knowledge regarding the tools, especially among safety and health personnel [96]. Furthermore, Sacks, Gurevich, and Belaciano. [93] stress the implementation and equipment costs as one of the main limitations of their VR system.

Additionally, the perception of distance is another limitation of using the VR headset identified in a study by Natephra et al. [82].

On a different issue, Jensen [102] states that visualising the avatars' body language should be considered to enhance collaboration within the VR scenario.

Lastly, most authors do not present detailed specifications regarding the computer hardware used. The performance of future VR tests, i.e., the quality of future replication studies, may depend on using the same hardware specifications. Hence, disclosing such information would contribute to the research field.

2.5.5 Introduction to Augmented Reality

Azuma [119] describes AR as a variation of VR, aiming to complement a real environment with the integration of virtual objects. Also, the author designates that AR systems hold three main characteristics: the combination of real and virtual; real-time interaction; and 3D presentation.

Chi, Kang, and Wang [120] and Wang et al. [121] determine that AR technology evolved from marker-based applications towards markerless systems. Still, more recent advances in context-aware tools, such as Wikitude [122], Google's Project Tango [123], and more recently, ARCore [55] and ARKit [54], may expedite the technology usage on mobile devices. In a study by Kodeboyina and Varghese [124], the fundamental requirements to develop AR systems are input devices, sensors, processor, and display, which are mostly integrated into modern handheld equipment such as smartphones and tablets. Indeed, there is a rising trend towards mobile AR [9], given the increasing processing power of handheld devices.

In their literature review, Rankohi and Waugh [9] discriminate articles on AR into three categories attending to the technology domain. Adapted from the authors' study, Table 8 summarises this classification.

Table 8 - AR categories regarding the technology domain [9].

Technology perspective	**Classification**
User experience	Immersive
	Non-immersive
Device	Mobile
	Stationary
Delivery	Web-based
	Standalone

From data collected until 2012, most research was based on non-immersive, stationary, and standalone AR systems. However, the authors allude to the advent of web-based, mobile AR applications [9].

In a study by Li et al. [125], a range of available AR systems and technologies is presented (e.g., Microsoft HoloLens, Epson Moverio BT-200, Vuzix M100, among others). Moreover, the authors categorise AR into three layers according to the technology characteristics: Tangible; Collaborative; and Distributed.

Tangible AR applications comprise real objects used to convey and interact with virtual information. Collaborative AR systems allow multiple users to be connected to the virtual simulation. Lastly, distributed AR, or network AR, comprise systems that allow remote users to interact in the same application.

2.5.6 Augmented Reality in the AECO sector

Although several AR applications have been registered over the years in fields such as the military, medicine, automotive, entertainment, advertising, and social communication, the technology is also being employed in the AECO sector [9], [121]. Nonetheless, research has documented limitations that still hamper the implementation of AR for construction-related activities.

Rankohi and Waugh [9] claim that precise localisation and monitoring are among the most limiting factors of AR employment in construction-related applications. Kodeboyina and Varghese state that a critical problem regarding AR pertains to tracking accuracy and real-time [124]. Furthermore, possible tracking discrepancies may cause user discomfort [124] and completely disable the efficiency of the system, especially within the AECO sector, where accuracy is of the utmost importance to the correct interpretation of construction information.

With regards to construction projects, Agarwal [126] indicates that AR implementation costs can be a limitation, although mitigated in the long run. Additionally, spatial alignment of real and virtual objects, as well as the development of applications, may limit the uptake of AR technology by the construction industry and related fields.

While AR may be understood as an extension of BIM towards on-site applications and construction works given its favourable visualisation interactive features [121], limitations may also be found when managing higher amounts of data, especially in the case of BIM data [33],[127], [128].

Nonetheless, examples of the usage of AR systems in the AECO sector have been reported in multiple domains such as Design and Project Monitoring [31], [129], [130], Construction Safety and Training [131]–[133], Facility Management [134]–[136], Education [137]–[139], Constructions Operations and Maintenance [140]–[142].

Chu, Mathews, and Love [31] mention the effectiveness of a BIM-based AR application in improving access to project information. Comparative tests were conducted, and results show that the AR interface, based on Quick Response (QR) markers, provided faster information retrieval, minimal errors, and therefore increased productivity than the more traditional approach.

Kim and Kang [129] proposed and implemented a BIM-based AR interface (marker-based) for drawing verification to increase the applicability of drawings to the actual site. The authors claim that construction projects have become increasingly complex and AR offers a more contextualised alternative, merging virtual representations into the real physical environment constraints where tasks occur.

In a study by Wang [132], a marker-based solution focusing on decreasing construction site layout planning errors is presented. The system allows for comparing different worksite arrangements and possible equipment collisions, supporting an overall fleet production verification.

Pereira, Gheisari, and Esmaeili [133] describe the use of an AR panoramic technique to develop a construction safety training application. Instead of displaying an artificial environment (i.e., a virtual 3D model), the proposed system overlaps safety information on top of 360º images, thus presenting safety-related information to users.

Regarding Facility Management, Olbrich et al. [136] developed a markerless AR application that generates BIM data from users’ on-site semantic annotations in place of more traditional paperworkbased approaches. The system uses mobile, markerless AR and position-tracking technology, allowing visualisation and automatic annotation update to the corresponding BIM model.

Hernandéz et al. [135] describe an alternative approach in self-inspection works that combines BIM data, AR, and IFC format, thus granting interoperability between software and allowing the participation of all stakeholders in the information exchange circle (on-site and off-site).

Behzadan and Kamat [137] describe pedagogical applications of marker-based AR systems to engineering education to convey real-time interactive, contextual and graphic information on equipment operations, jobsite safety, resource utilisation, work sequencing, and site layout.

Zhou, Luo, and Yang [142]developed a tunneling inspection operation framework to compare the as-built segment displacement with the augmented model. The system was chosen over laser-scanning, Kinect, and binocular camera (depth-sensing) options, and results demonstrate that the AR method is faster and more intuitive than the traditional approach (manual measurements). Feedback from a focus group corroborates the findings that the AR approach is favourable for inspection operations.

In a study by Wang et al. [121], Architecture/Design and Construction (on-site work) were identified as the top adopters of AR within the construction sector. It is also reported that the construction sector displays more interest in AR when compared to VR, given the portability and context-related features of the technology, making it suitable to be used on the construction site.

Rankohi and Waugh [9] conducted a statistical literature review on the stage of maturity of AR technologies in AECO applications focused on publications made between 1999 and 2012. The authors concluded, among other aspects, that most studies were focused on the construction or maintenance phase, with workers being the most widely targeted group. Furthermore, visualisation/simulation and communication/collaboration were the primary areas of application. Also, noticeable interest in the technology was reported among project managers and field workers. The document also reports that case studies were the most applied research method. Finally, the authors state that future AR systems will relate to mobile, collaborative, and internet applications. Additionally, industry practitioners might value more friendly interfaces, quicker return on investment, and information integration (such as BIM integration) [9].

AR applications enriched with BIM information are proven beneficial to different applications in the AECO sector. Indeed, AR has been targeted as one of the main BIM-related research fields [143]. Current examples of BIM-based AR applications may be found in the studies of [31], [33], [127]–[129], [136].

Considering that few BIM-based AR applications have been reported in previous literature reviews, there is a requirement for an overview of the most recent body of knowledge targeting BIM-based AR interfaces. A systematic literature review is presented in the following sections for a more comprehensive understanding of such interfaces and their role in the AECO sector. Furthermore, and similarly to the systematic review conducted on BIM-based VR, this study provides a full-fledged appraisal of the most current methods, reasoning, tools (i.e., hardware and software), target groups, and assessment methods used to develop BIM-based AR applications.

2.5.7 BIM-based AR systematic literature review

A growing interest and increasing number of applications in the context of AECO in association with BIM methodology have been verified as AR is reported as one of the main BIM-related research fields [143]. Therefore, this section intends to fill the gap for a systematic review to comprehensively understand BIM-based AR applications by answering a list of critical research questions (Table 9).

Table 9 - Research questions.

Q1	What are the AR techniques implemented in construction projects?
Q2	What is the purpose of BIM-based AR implementation in construction projects?
Q3	At which stages of the Project lifecycle are the AR techniques implemented?
Q4	Are AR techniques improving more traditional approaches?
Q5	What are the limitations of BIM-based AR, and are they being solved in recent research?
Q6	What are the main target groups?
Q7	How are these interfaces being assessed (e.g., qualitative, quantitative, comparative assessments, case studies, usability assessments)?
Q8	What are the mainly researched BIM dimensions?

The methodology applied to carry out this systematic review is based on PRISMA-P [144]. In the present review, this reference is used as a methodology protocol to comply with PRISMA [114]. All applicable research steps are described in the section herein, i.e., information sources, search strategy, inclusion and exclusion criteria, and the main tools to assess the bias within the eligible studies. Adjustments regarding the original protocol [144] were necessary concerning the year range for the review. In particular, after finding evidence [9], the review scope changed from 2016-2020 to 2013-2020.

In the research phase, 671 papers were collected. From these, 255 were immediately excluded for being duplicates. Afterwards, throughout the application of the exclusion criteria, 376 articles were removed. These comprised 82 articles excluded by date (publication date prior to 2013); 239 excluded due to paper type (reviews, letters, books, and surveys were rejected); four excluded by source (as standard procedure, only journals were accounted for, as they stand as the most significant providers of scientific content); 12 excluded by language (papers written in languages other than English were rejected); 39 excluded for being off-topic. The resulting 40 articles were assessed for eligibility, from which 16 were rejected since they did not comply with the proposed objectives nor refer to the use of a BIM-based tool. Figure 14 summarises the research process, adapted from Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) [145], where a final count of 24 papers can be seen.

Table 10 - Exclusion criteria and the corresponding number of articles excluded.

Exclusion Criteria	**Number of articles excluded**
Articles released prior to 2013	82
Non-journal articles	243
Non-English articles	12
Off-topic articles	39
Articles manually identified as duplicates	255
Total number of articles excluded	**631**
Remaining articles	**40**

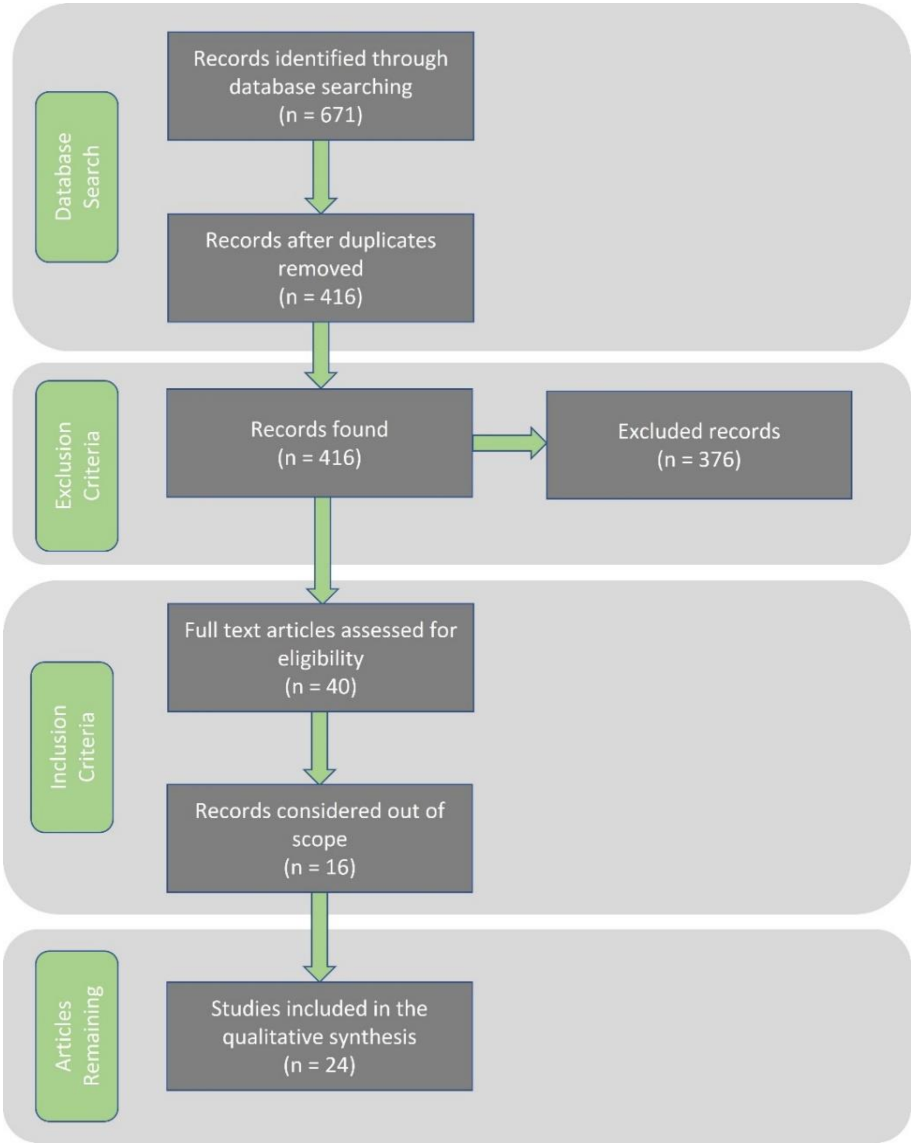

Figure 14 - Strategy for the selection of relevant articles for the BIM-based AR systematic literature review, adapted from [146].

Bias in a study is considered any inclination or interference that can keep it from being considered undeniable concerning a problem [147]. A repetitive error presented in sampling, testing, or analysis, as well as indirectly or directly supporting one result, is also considered bias [148]. In the selected articles for this study, the existence of "selection bias" may be argued. Selection bias is proven as a statistical miscalculation caused by an incorrect sample selection in an experiment or an investigation [148]. When present, selection bias obstructs the proper representation of the analysed group, possibly affecting the study results [148]. In the case of this review, some studies had a small sample of 10 individuals, which were used to perform case studies followed by questionnaires. Given the significant difference in the individuals' characteristics and experiences over such a small sample, a slight negative impact on the conclusions can be expected.

It should be mentioned that the "selection bias" does not dismiss the entire article or its conclusions. Conversely, it emphasises the need for critically analysing the article's framework and results. For instance, although usability results may be affected, the article proposed solutions, working methods, and functionalities (on which the present review is mainly focused) may not be entirely affected.

Meanwhile, no articles were excluded as the possible presence of bias did not affect the proposed research questions.

The arrangement of the review starts by classifying the included articles, demonstrating the general characteristics of the studies, illustrating their objectives, and pointing out the essential information to answer the previously formulated research questions (Table 9). The following sections show the contents of the studies, as well as identified trends and research limitations.

Characteristics of the included studies

This section summarises the 24 articles included in the review to identify the most contributing authors and list the frequent journal publications.

The screened publication period included 2013 to 2020, with more than half of the publications released between 2018 and 2020. The selected studies revealed an average of 26,57 citations per article, calculated from the available bibliography at the time of writing.

Concerning the keywords, 113 occurrences were identified, combined in 13 clusters. The core subjects of the research, i.e., AR and BIM, are strongly linked with fields such as Construction, Mixed Reality, Automation, Information and Communication, Facility Management and Quality, among others, as depicted in Figure 15. Additionally, it was noticed that the subjects: Construction Assemblies, Cloud-based, Image Retrieval, Sensors, Error Estimate, Tracking, Information, and Construction Industry are frequently occurring in the most recent articles (data collected using VOSviewer [149] and not entirely noticeable in Figure 15 due to the software zoom setting limitations).

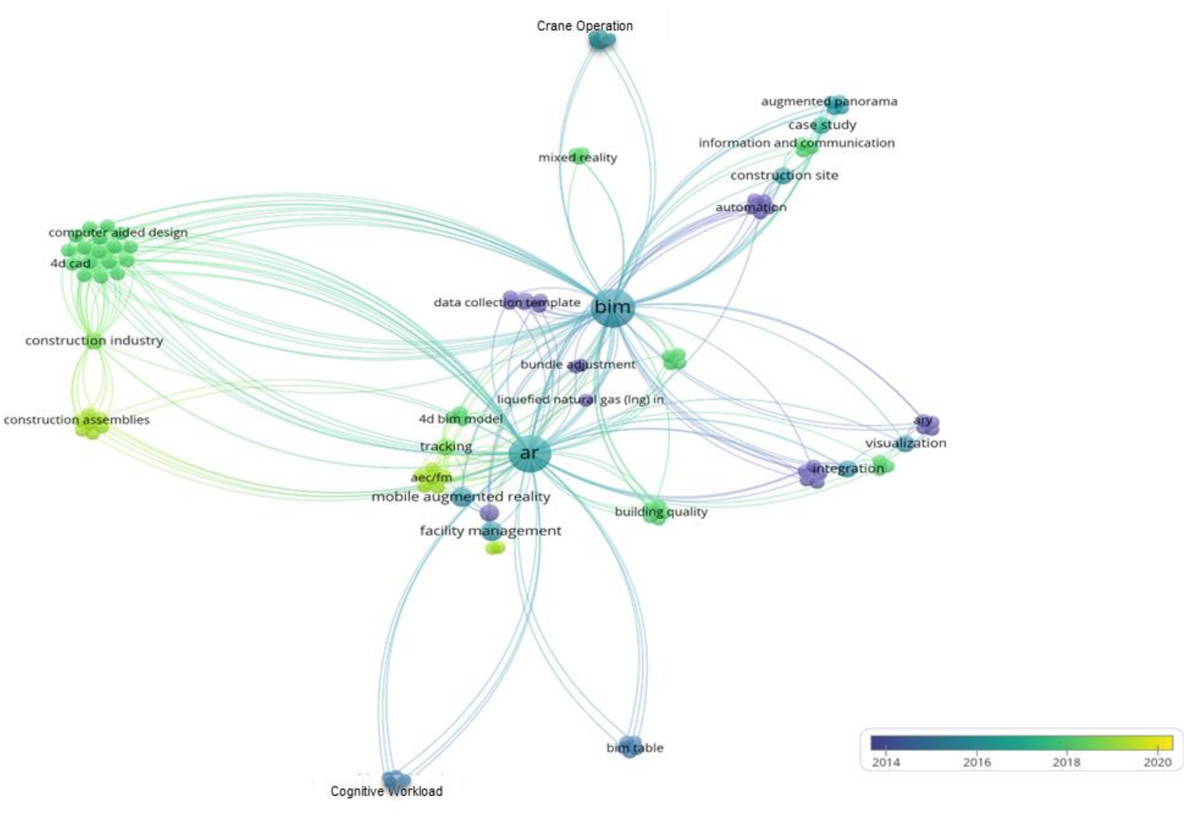

Figure 15 - Keyword connections, adapted from [146].

Analysis of the construction stages

This section reports identified construction stages among the screened articles. Construction was the main occurring stage, targeted by 87.5% of the selected articles, which is aligned with previous review

studies [9]. Pre-Construction appears in the second position, with ten occurrences, followed by Design, with nine occurrences. Finally, Operation and Management is the least focused stage, with six occurrences.
Figure 16 displays an overview of the screened BIM-based AR applications throughout different construction stages.

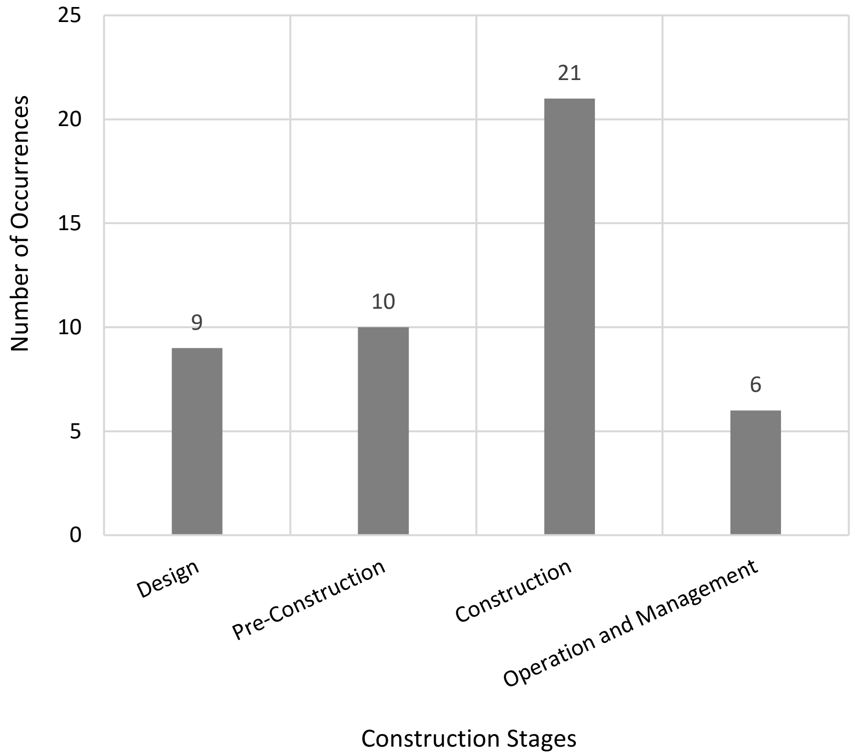

Figure 16 - Presence of BIM-based AR applications in construction stages, adapted from [146].

These results contrast significantly with the previous review focused on BIM-based VR (cf. section 2.5.4, *Analysis of the construction stages*), where Design was the most researched stage.

Fields of implementation

Regarding the fields of implementation, seven unique research fields were identified:

- Collaboration – mainly focused on communication, teamwork, and cross-team interaction;
- Construction Design – regards the Design stage of a construction project;
- Construction Management – considers the management of a construction project throughout the Design and Construction stages. This field was further divided into two subfields, namely:
    a. Quality Control – management tasks such as site quality inspection and defect prevention;
    b. Site and Resource Control – management tasks such as workplace planning, crew performance, schedule tracking, and report management.
- Construction Safety – construction site safety-related tasks and operations, mainly through increased awareness and improved design;
- Education – field focused on improving the knowledge of any construction-related entity such as workers, engineers, architects or students;

- Facility Management – field related to the management of a facility in the course of the operations stage;
- Worker Performance – concerns improvements in the workers' onsite performance, namely through task guidance or efficiently delivering information that would otherwise be difficult to acquire.

The fields of implementation were classified as primary or secondary, depending on their importance in each article (i.e., bold fields in .

Table 11 were classified as primary, while the remaining were classified as secondary).

As part of Construction Management, Site and Resources Control is the most researched field, exhibiting a total of 16 occurrences as either primary or secondary [31], [135], [158]–[163], [150]–[157]. Meža, Turk, and Dolenc [162] and Kim et al. [150] research aims to improve the availability and usability of BIM information on the construction site through AR by overlapping the scheduled BIM model and the actual construction state. Information such as costs may also be accessed using the mentioned interfaces. Case studies were carried out in both articles, with the authors concluding that the interfaces facilitate fieldwork monitoring and support cooperation and decision-making.

Quality Control was identified in ten articles [31], [135], [152], [153], [155], [158]–[161], [163] followed by Construction Design [31], [151]–[154], [157], [159]–[161] with nine occurrences.

Both Park et al. [158] and Kwon et al. [155] explored Quality Control, presenting defect management systems using image-matching and AR. These systems were tested in laboratory experiments (using mock-up models) and during real-site experiments, proving the systems' effectiveness. Despite this, using markers for the image-matching process was identified as potentially problematic due to the large number of markers required, and time-consuming angle calibration.

Regarding Construction Design, Rahimian et al. [160] developed an AR application that enables the immersion of its users into a building's design, allowing for a better knowledge of the complex spatial distributions of buildings, as well as its related physical and non-physical constraints. The application also enables other design options, such as changing elements, materials and aesthetic properties.

A total of 8 articles focused on the field of Collaboration, although mostly as a secondary field [31], [151]–[154], [157], [159], [160]. However, a study by Lin et al. [154] presents collaboration as a primary field. The authors focused on enhancing the cooperation and communication between project entities through an AR and multiscreen (AR-MS) system. The system includes an original stationary piece of hardware, a BIM Table, that enables an efficient collaboration among disciplines by providing an accurate and time-saving user interface, reducing the complexity of discussions, and keeping necessary information available during the entire process. Through user tests and questionnaires, the authors acquired positive feedback when comparing the novel system to conventional methods of communication within construction projects.

Four occurrences were noticed concerning the field of Worker Performance [161], [164]–[166]. Hou, Wang, and Truijens [166] and Chalhoub and Ayer [164] devised approaches to increase the productivity and output quality of workers by inserting digitalised information into the real-world workspace using AR. The added information allows workers to implement correct assembly procedures with improved accuracy and reduced errors. In particular, Hou, Wang, and Truijens [166] focused on piping assemblies, while Chalhoub and Ayer [164] concentrated on electrical conduit assemblies. Through user tests and questionnaires, both studies report positive feedback when comparing the proposed systems to conventional communication methods within construction projects, leading to higher productivity rates, shorter task completion times, and fewer assembly errors.

Construction Safety is verified in two publications [156], [167], followed by Education [156], [167], [168] recognised in three.

Park and Kim [167] present an original framework for safety management and visualisation that integrate BIM, location tracking, AR, and game technologies, within its architecture. Also, the application includes an education module that instructs the workers on the safety risks related to different work activities. The authors concluded that the system is appropriate for fieldwork after performing interviews and applying the prototype system to a real-case scenario. The results demonstrate the proposed solution's effectiveness in supporting communication and identifying insecure working environments and unsafe actions while dynamically assisting decision-making.

Facility Management was identified in six articles as the primary field [31], [159], [160], [169]–[171]. Chu, Mathews, and Love [31] mention the effectiveness of a BIM-based AR application in improving access to project information. Comparative tests were conducted, and results show that the AR interface, based on Quick Response (QR) markers, provided faster information retrieval, minimal errors, and increased productivity compared to the more traditional approach.

A low-cost approach based on mobile AR is described by Williams et al. [171]. The system enables users to conduct facility management tasks through a handheld device on which BIM information is displayed over the real objects in the room using the device's camera. Results from the user-centred evaluation support that the system is fairly easy to use, despite the verified drift and mismatch between real and virtual objects.

Analysis of the target groups

Eight main target groups were identified in the screened articles: architects, construction managers, design engineers, facility managers, owners, safety managers, students, and workers. However, in alignment with the research field analysis, the construction managers were further divided into two
An emphasis in the Construction phase was identified as most occurrences were related to site and resources controllers, workers, and quality controllers. Additionally, these findings differ from the previous VR systematic review (cf. section 2.5.4, *Analysis of the target groups*), where, aside from engineers, architects, workers, and owners, were the most occurring target groups.

Analysis of the use of BIM dimensions

BIM dimensions can be used to characterise a BIM approach or model, i.e., the information available to the user [109], as each dimension is responsible for a pre-established data set. However, since this topic lacks general agreement, mostly beyond the 5th dimension (cf. Charef, Alaka, and Emmitt [172], and Smith [116]), this study is in line with the definitions presented in section 2.5.4. Furthermore, the present review aligns with the research conducted by Kamardeen [117], which proposes extending BIM to an 8th dimension so that safety knowledge (e.g., prevention and risk assessment aspects) can be thoroughly included through design and construction stages. As such, this review considers BIM dimensions as follows:

- 3D – Shape;
- 4D – Scheduling;
- 5D – Costs;
- 6D – Facility Management;
- 7D – Sustainability;

- 8D – Safety.

The analysis of the screened papers revealed that 3D is the most exploited dimension, verified in all articles. Nonetheless, the remaining dimensions are still significantly overlooked. 7D was not directly targeted by any author. Furthermore, only 25% of the reviews exploited three dimensions simultaneously, with none utilising four or more. Overall, results display a lack of diversity in exploring BIM dimensions.

Table 11 presents an outline of the verified construction stages, fields (i.e., primary (bold) or/and secondary), corresponding target groups and identified BIM dimensions.

Table 11 – Construction stages, fields, and target groups of the screened articles, based on [146].

Authors	**Title**	**Construction Stage**	**Fields**	**Target Group**	**BIM Dimension**
Hyojoon Bae; Mani Golparvar-Fard; Jules White	High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications	Design Pre-Construction Construction Operation and Management	**Collaboration** **Construction Design** **Facility Management** CM - Quality Control CM - Site and Resources Control	Architects CM - Quality Controllers CM - Site and Resources Controllers Design Engineers Facility Managers Owners Workers	3D 6D
Chan-Sik Park; Do-Yeop Lee; Oh-Seong Kwon; Xiangyu Wang	A framework for proactive construction defect management using BIM augmented reality ontology-based data collection template	Construction	**CM - Quality Control** **CM - Site and Resources Control**	CM - Quality Controllers Workers CM - Site and Resources Controllers	3D
Yi Jiao; Shaohua Zhang; Yongkui Li; Yinghui Wang; BaoMing Yang	Towards cloud Augmented Reality for construction application by BIM and SNS integration	Design Pre-Construction Construction	**CM - Site and Resources Control** Collaboration Construction Design	Design Engineers CM - Quality Controllers CM - Site and Resources Controllers	3D 4D 5D
Chan-Sik Park; Hyeon-Jin Kim	A framework for construction safety management and visualisation system	Pre-Construction Construction	**Education** **Safety**	Safety Managers Workers	3D 4D 8D
Xiangyu Wang; Martijn Truijens; Lei Hou; Ying Wang; Ying Zhou	Integrating Augmented Reality with Building Information Modeling: Onsite construction process controlling for liquefied natural gas industry	Construction	**Education** **Safety** CM - Site and Resources Control	CM - Site and Resources Controllers Safety Managers Workers	3D 4D 8D
Oh-Seong Kwon; Chan-Sik Park; Chung-Rok Lim	A defect management system for reinforced concrete work utilising BIM, Image matching and augmented Reality	Construction	**CM - Quality Control** **CM - Site and Resources Control**	CM - Quality Controllers CM - Site and Resources Controllers	3D 4D
Sebastjan Meža; Žiga Turk; Matevž Dolenc	Component based engineering of a mobile BIM-based augmented reality system	Construction	**CM - Site and Resources Control**	CM - Site and Resources Controllers	3D 4D

Authors	Title	Construction Stage	Fields	Target Group	BIM Dimension
Graceline Williams; Masoud Gheisari; Po-Jui Chen; Javier Irizarry	BIM2MAR: An Efficient BIM Translation to Mobile Augmented Reality Applications	Operation and Management	**Facility Management**	Facility Managers	3D 6D
Lei Hou; Xiangyu Wang; Martijn Truijens	Using Augmented Reality to Facilitate Piping Assembly: An Experiment-Based Evaluation	Construction	**Enhance Worker Performance**	Workers	3D
Tin-Hui Lin; Chao-Hsiang Liu; Meng-Han Tsai; Shih-Chung Kang	Using Augmented Reality in a Multiscreen Environment for Construction Discussion	Design Pre-Construction Construction	**Collaboration** CM - Site and Resources Control Construction Design	Architects CM - Site and Resources Controllers Design Engineers Owners Workers	3D 4D
Yi-Chen Chen; Hung-Lin Chi; Shih-Chung Kang; Shang-Hsien Hsieh	Attention-Based User Interface Design for a Tele-Operated Crane	Construction	**Enhance Worker Performance**	Workers	3D 4D
Masoud Gheisari; Mohsen Foroughi Sabzevar; Pojui Chen; Javier Irizzary	Integrating BIM and Panorama to Create a Semi- Augmented-Reality Experience of a Construction Site	Design Pre-Construction Construction	**CM - Quality Control** **CM - Site and Resources Control** **Construction Design** Collaboration	Architects CM - Quality Controllers CM - Site and Resources Controllers Design Engineers Owners Workers	3D
Zhengbo Zou; Luiz Arruda; Semiha Ergan	Characteristics of models that impact the transformation of BIMs to virtual environments to support facility management operations	Operation and Management	Facility Management	Facility Managers	3D 6D
Michael Chu; Jane Matthews; Peter E.D. Love	Integrating mobile Building Information Modelling and Augmented Reality systems: An experimental study	Design Pre-Construction Construction Operation and Management	**CM - Quality Control** **CM - Site and Resources Control** **Facility Management** Collaboration Construction Design	Architects CM - Quality Control CM - Site and Resources Controllers Design Engineers Facility Managers Owners Workers	3D 6D
Mohamed Zaher; David Greenwood; Mohamed Marzouk	Mobile augmented reality applications for construction projects	Design Pre-Construction Construction	**CM - Site and Resources Control** **Construction Design** CM - Quality Control Collaboration	Architects CM - Quality Controllers CM - Site and Resources Controllers Design Engineers Owners	3D 4D 5D

Authors	Title	Construction Stage	Fields	Target Group	BIM Dimension
José L. Hernández; Pedro Martín Lerones; Peter Bonsma; Andrè van Delft; Richard Deighton; Jan-Derrick Braun	An IFC Interoperability Framework for Self-Inspection Process in Buildings	Construction	**CM - Quality Control** **CM - Site and Resources Control**	CM - Quality Controllers CM - Site and Resources Controllers	3D
Jad Chalhoub; Steven K. Ayer	Using Mixed Reality for electrical construction design communication	Construction	**Enhance Worker Performance**	Workers	3D
Duanshun Li; Ming Lu	Integrating geometric models, site images and GIS-based on Google Earth and Keyhole Markup Language	Design Pre-Construction Construction	**Construction Design** **CM - Site and Resources Control** Collaboration	Architects CM - Site and Resources Controllers Design Engineers Owners	3D 4D
Hyeon Seung Kim; Sung-Keun Kim; Andre Borrmann; Leen Seok Kang	Improvement of Realism of 4D Objects Using Augmented Reality Objects and Actual Images of a Construction Site	Construction	CM - Site and Resources Control	CM - Site and Resources Controllers Workers	3D 4D 5D
Ozan Koseoglu; Elif Tugce Nurtan-Gunes	Mobile BIM implementation and lean interaction on construction site: A case study of a complex airport project	Construction	**CM - Quality Control** **CM - Site and Resources Control**	CM - Quality Controllers CM - Site and Resources Controllers	3D 4D 5D
Valentin Gomez-Jauregui; Cristina Manchado; Jesús Del-Castillo-Igareda; Cesar Otero	Quantitative evaluation of overlaying discrepancies in mobile augmented reality applications for AEC/FM	Design Pre-Construction Construction	**Enhance Worker Performance** **Construction Design** **CM - Quality Control** **CM - Site and Resources Control**	Architects CM - Quality Controllers CM - Site and Resources Controllers Design Engineers	3D
Fopefoluwa Bademosi; Nathan Blinn; Raja R. A. Issa	Use of augmented reality technology to enhance comprehension of construction assemblies	Construction	**Education**	Students	3D
Francis Baek; Inhae Ha; Hyoungkwan Kim	Augmented reality system for facility management using image-based indoor localisation	Operation and Management	**Facility Management**	Facility Managers	3D 6D
Farzad Pour Rahimiana; Veselina Chavdarova; Stephen Oliver; Farhad Chamo; Lilia Potseluyko Amobi	OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing	Design Pre-Construction Construction Operation and Management	**Construction Design** **Facility Management** **CM - Quality Control** **CM - Site and Resources Control** Collaboration	Architects CM - Quality Controllers CM - Site and Resources Controllers Design Engineers Facility Managers Owners Workers	3D 6D

System architecture, employed software and hardware

Compared to the system architecture of BIM-based VR interfaces described in section 2.5.4, the revised papers do not exhibit a shared technological approach for BIM-based AR interfaces. Indeed, a wide variety of approaches are applied in current research, thus rendering the definition of general components organisation, system architecture, or an overarching framework unfeasible. Although the scope of this thesis deviates from proposing a holistic framework for AR implementation in the AECO sector, the studies conducted by Nassereddine et al. [173], Steffen et al. [174], and Berkemeier et al. [175] regarding AR implementation are worthy of mention.

Nassereddine et al. [173] present a framework for integrating AR into the construction phase providing AECO actors with an improved understanding of the technology's potential and suitability to overcome some industry barriers. The framework maps the relationship between AR capabilities and potential benefits based on 23 use cases.

Steffen et al. [174] propose a framework based on the affordances of virtual technologies (i.e., VR and AR) that prompt users to virtualise tasks. The framework is based on the concept of affordances as being more generalisable than focusing on specific uses and activities and allows a comparison between the affordances of traditional activities and those capitalising on virtual environments (i.e., VR and AR-based). Additionally, a comparison is established among related activities based on VR and AR.

Steffen et al. [174] also allude to the significant technological challenges that may hinder VR and AR general uptake and the possible lack of a full understanding by the practitioners and researchers regarding the affordances and motives that would determine a wide adoption of the technology. Moreover, a lack of research concerning the motivation that guides large-scale AR (as well as VR) adoption is reported.

Berkemeier et al. [168] described a framework and design principles towards developing AR glasses-based systems applied to the intralogistics domain. The framework comprises five stages (i.e., initialisation, potential assessment, requirements analysis, design, and implementation) and a formative evaluation acting as a standard for alignment, enhanced feedback, and fast prototyping based on a series of iterations. Moreover, the proposed framework uses the concept of gates (i.e., viability gate, feasibility gate, and desirability gate) as milestones that potential solutions must overcome to reach implementation. As to design principles, 12 design principles are mentioned towards developing AR glasses-based systems (e.g., modular design, attending to users' qualifications, user-friendly layouts, acceptance as a design goal, privacy, and safety considerations, providing system feedback and various interaction methods, consideration of device limitations). Also, Berkemeier et al. [175] advocate that AR glasses-based systems architecture should be hosted on the cloud to provide access independently of the users' location and maintain the AR-glasses processing as low as possible.

It is also noteworthy to mention research conducted by Chi, Kang, and Wang [120] describing features of AR and their essential associated devices. The authors refer to four primary stages of the system architecture of an AR application and their related technologies, namely:

i) Data – Cloud Computing Environment – (BIM, database, service-oriented architecture (SOA), internet);

ii) Computing – Localisation Technologies (Global Positioning System (GPS), Ultra-wide-band (UWB), Simultaneous Localisation and Mapping (SLAM), Radio Frequency Identification (RFID), barcode);

iii) Tangible– Portable and Mobile Devices (cheap, small, light, wearable and ubiquitous), and i.v) Presentation – Natural User Interface (gesture, kinesthetic, intuitive control, motion capture).

As a result of a comparison with the previous four stages, it was found that most screened AR systems contain some of these elements. For instance, cloud computing environments have been recognised in server-based applications in seven [31], [135], [151], [152], [157], [162], [171] out of 24 revised papers.

Also concerning technological approaches, most AR interfaces describe markerless methods as 11 [150], [151], [171], [152], [153], [160], [162], [164], [165], [168], [169] out of 24 articles adopt this type of technology. The most recent papers (2018, 2019 and 2020) report developments on this type of technology in lieu of maker-based applications [31], [151], [170].

There is a wide variety of applied localisation technologies, depending on the system's specifications and the application or task itself.

Regarding portable and mobile devices and NUIs, tablets and smartphones were preferred. In particular, Android-based solutions were verified in eight papers [31], [135], [152], [154], [159], [164], [170], [171], and iOS-based systems were confirmed in five articles [153], [156], [157], [159], [171]. Other applications tend to rely on gesture-based interfaces using the features of HMDs, such as Microsoft Hololens [164].

With regards to software, Revit appeared as the BIM tool of choice with nine occurrences [31], [135], [152], [153], [159], [164], [169]–[171], followed by ArchiCAD with 2 [155], [158].

Unity was the only game engine used to develop and convey virtual environments across a variety of platforms [153], [159], [170], [176].

Evaluation and assessment

Most screened papers present a validation method to ascertain the suitability of the proposed BIM-based AR systems. However, a comparative analysis of the various solutions was considered rather challenging despite the numerous approaches used (e.g., interviews, laboratory performance tests, and usability assessments).
Case studies were performed in 17 out of 23 publications [31], [135], [164], [167], [168], [171], [176]–[178], [150], [151], [153], [154], [156]–[158], [160] of which four describe user tests [31], [150], [154], [168].
Performance assessments and laboratory validations were identified in nine publications [151], [152], [155], [157], [159], [160], [165], [169], [176].
Eight studies state the collection of data through questionnaires [153], [154], [157], [160], [162], [165], [166], [168], while complementary data collected from interviews was identified in three other publications [155], [166], [167].
Two case studies [153], [171] also report using the think-aloud approach, where users' feedback from testing the system is directly recorded.
Lastly, usability assessment is directly mentioned in four studies [153], [154], [160], [166].

Verified limitations and future work recommendations

AR technology is evolving from static information associated with an object entity to context-aware systems that recognise the surrounding environment [121]. From early AR systems initiatives to construction inspection and architecture renovation, such as the one proposed by Webster et al. [179], to the more recent HMD-based applications (e.g., Microsoft HoloLens, Magic Leap), several research studies have demonstrated a generalised interest towards the use of AR systems to the domains of the AECO sector. Indeed, Dong and Kamat [180] assert that visualisation, information retrieval from BIM for communication, and interaction of virtual models with the real scenario represent some of the advantages that AR may bring to the construction sector and related fields over different visualisation practices. In particular, for Civil Engineering, AR may reduce construction errors and project design review; improve communication compared to traditional 2D approaches; provide time-savings and cost reductions, as described by Agarwal [126].

The integration of AR into future developments may be faced with persisting technical challenges, such as the need for reduction of implementation costs; spatial alignment of real and virtual objects [126], [180]; improvement of tracking accuracy [124] and occlusion (the illusion of co-existence of real and virtual elements) [180].

Concerning BIM-based AR, limitations were mostly found in the data transfer due to the dependence on effective internet connectivity and GPS connection. Bae, Golpavar-Fard, and White [159] present an alternative approach to detect the user's location based on comparing mobile devices' photographs with a 3D point-cloud model, thus being independent of external modules to track the user's positioning. Recent approaches, such as World Locking Tools [181], may provide alternatives to persisting AR content in real space.

A lack of full integration of non-geometric information into AR interfaces was also noticed. Therefore, interoperability between BIM software and AR systems still requires further developments to combine building semantic information seamlessly. Indeed a need for a stable and effective pipeline to transfer BIM information to mobile and web-AR is still persistent, as emphasised by Willians et al. [171]. Additionally, the authors highlight that BIM-based AR research should consider the users' experience in the real world and their knowledge. This perspective is aligned with research conducted by Edirisinghe [177] and Wang et al. [121]. Edirisinghe [177] mentions that technology should consider the users' experience in the real world and their knowledge regarding target-specific domains. Simultaneously, Wang et al. [121] stress implementing the AR system into real construction projects as a future perspective.

Regarding future works, a framework for implementing AR technologies in the AECO industry was found absent, as well as a common assessment method to check the effectiveness and usability of the applied AR tools.

Finally, although AR tools are being researched and tested in the academic field, their implementation in practical construction projects remains to be fully established. From the included articles, it can be assumed that the relationship between AR and BIM is still in the early stages of development and application. Indeed, all articles described experimental approaches, indicating potential and favourable results. However, the research did not show a stable output, and adoption by the AECO sector is still limited to early adopters.

2.5.8 Summary

This section intends to present the literature research results regarding innovative interfaces applied to the AECO sector, particularly the state of the art of BIM-based VR and AR applications. Overall, from the literature research, it can be determined that despite the well-known resistance of the AECO industry in the uptake of new approaches and technologies, VR and AR systems are permeating amidst several construction-related domains.

The conclusions of the systematic literature reviews are described below, organised into two tables, Table 12 and Table 13. The structure of each table corresponds to answers to the research questions presented in sections 2.5.4, Table 2, and 2.5.7, Table 9, respectively.

Conclusions from the literature review on BIM-based VR in the AECO sector

Regarding VR, the systematic review included only journal articles (written in English) that met three core criteria:

(i) An immersive VR application;
(ii) BIM-based VR systems; and
(iii) An assessment method for the proposed application.

The analysis provided answers to the initial 11 research questions presented in 2.5.4, Table 2.

Table 12 - Answers to the research questions.

Q1	What is the purpose of VR implementation in construction projects?
A1	VR applications have verified benefits amongst construction stakeholders, improving collaboration and communication, and providing a means for people with different construction knowledge to access BIM information.
Q2	What is the main framework and system architecture being used?
A2	A three-layer architecture was identified in most papers. A BIM authoring tool to provide accurate 3D geometry to the system; a visual enhancement tool to optimise the model and overcome interoperability issues between the BIM tool and the last layer – the game engine; and the game engine component to enable core functionalities for the development of the virtual environment. One aspect worth mentioning is the presence of a fourth layer, in some articles, regarding a database connection to allow the transfer of non-geometric information between the BIM authoring tool and the immersive virtual environment. Multiuser immersive interfaces were also identified, although in fewer occurrences. This type of interface requires a network connection to enable several users to be present in real-time within the virtual scenario.
Q3	Why are applied interfaces and the respective tools selected?
A3	Most articles do not provide enough reasoning for the selection of the tools, nor do they describe hardware specifications despite their potential impact on the system's performance. Nevertheless, it can be stated that cross-platform compatibility and the existence of an active support community were the main reason stated for the software selection. Concerning hardware, most authors underpin their selection according to immersiveness, affordability and available functionalities.
Q4	At which stage of the project's lifecycle is VR being implemented?
A4	Design, Pre-construction, Construction, and Operations and Management were the main stages of the projects' lifecycle where VR is currently being implemented. Furthermore, Design was verified in 12 articles, while the remaining stages were confirmed in nine papers.
Q5	How are these interfaces being assessed?
A5	Case studies were the most identified assessment method (12 articles), accompanied by questionnaires in half of the articles screened. To ease user interaction with the developed systems, previous trials (i.e., pilot tests) were verified in three papers.
Q6	What are the main target groups?
A6	The main target groups focused on the articles were engineers, architects and workers. Furthermore, owners, facility managers, end-users and students were also mentioned, although with little emphasis.
Q7	What are the main limitations?
A7	The main limitations identified comprise the developing efforts needed to develop the BIM model, interoperability hurdles between software and compatibility between software-hardware, and issues related to the poor graphics output quality and frame counting that may decrease the level of realism of the interfaces.
Q8	Were the limitations solved by later studies?
A8	Although limitations have been stressed, such as interoperability issues between software tools [91],[92], current studies describe viable applications for integrating BIM and VR. The latest commercial and open-source solutions provide near-instant VR experiences in the form of plugins

	developed to work within BIM authoring tools or as libraries or toolkits to be used by programmers (e.g., IrisVR [183], Revizto [184], Fuzor [185], Autodesk Live [186], Unity Reflect [187], BIMXplorer [188], ifcOpenShell [189]). Furthermore, recent publications on the bidirectional data exchange of BIM-VR interfaces have been developed [84], [111], [112], [190]. Moreover, to overcome vendor-format dependencies, the latest developments have been explored on IFC-based solutions enabling access to BIM parametric information within VR environments. Tridify [191] is a commercially available solution, IFC-based, developed to outrun BIM and game engines' interoperability issues. Academic works, such as research developed by Nandavar et al. [192], describe a system compliant with openBIM philosophy (IFC-based) to enable BIM-VR bidirectional geometric and parametric data exchange. The application provides VR scenario interactions such as measurements, parametric information visualisation, object geometric edition and elimination, as well as the saving and synchronisation of editions made in the immersive environment based on the IFC format.
Q9	How is BIM related to VR?
A9	BIM provides precise geometric information, which is widely used by the VR systems described within the screened papers. Therefore, the main relationship between BIM and VR occurs from the exchange of geometric data, also known as the third dimension of BIM.
Q10	What are the mainly researched BIM dimensions?
A10	The most applied dimension was 3D, followed by 4D.
Q11	Is BIM achieving its full potential with VR?
A11	The fact that most of the articles analysed are not related to a large part of the dimensions of BIM emphasises the need for more research on frameworks capable of enhancing the relationship between the technologies. Integrating non-geometric information into the immersive systems provides a much broader set of applications than only those made possible by interaction with the geometric model. Therefore, in the author's opinion, the potential of BIM integration with VR is still in its infancy and requires more research and implementation means, given the known benefits.

Conclusions from the literature review on BIM-based AR in the AECO sector

Regarding AR, the systematic review included only journal articles (written in English) that met two core criteria:

(i) BIM-based AR systems; and
(ii) An assessment method for the proposed application.

Table 13 presents answers to the initial eight research questions in section 2.5.7, Table 9.

Table 13 - Answers to the research questions.

Q1	What are the AR techniques implemented in construction projects?
A1	AR provides unique features that facilitate its application in the construction field. Most applications found in the literature review resort to markerless AR, despite the apparent ease of use of marker-based AR approaches. Additionally, Data Cloud computing environments have been recognised in server-based applications, as well as a wide variety of applied localisation technologies, dependent on the specifics of the system. the application or the task itself. Mobile devices and touch-based interfaces (i.e., tablets and smartphones) were recognised as the authors' preferred approaches, while the potential of gesture-based interfaces and HMDs were also reported (e.g., applications based on Microsoft HoloLens). BIM authoring tools such as Revit and ArchiCAD, as well as game engines (e.g., Unity), are used to support data transfer and the development of virtual environments.
Q2	What is the purpose of BIM-based AR implementation in construction projects?
A2	AR is mostly implemented on construction sites due to the visualisation and information extraction capabilities that it can provide. Moreover, current handheld devices meet the processing power needed to support AR applications, making them suitable for dynamic and cluttered settings such as construction sites. Included papers discuss how BIM-based AR applies to the construction site by supporting task

completion and reducing construction errors [153], [165], lowering cognitive workload [165], improving access to project information [177], management of construction schedules and costs [157], enhancing collaboration [153], increasing site assistance [31], safety training [157], task orientation [165], as well as higher productivity [176].

Q3 At which stages of the Project lifecycle are the AR techniques implemented?

A3 A significant number of the analysed studies focused on the Construction stage, with a total of 21 occurrences. Among the remaining stages, with ten occurrences and nine, respectively, are Pre-Construction and Design.

Operation and Management is the least focused stage, with six occurrences.

Q4 Are AR techniques improving more traditional approaches?

A4 More conventional approaches benefit from AR applications' support, although there is a recognised need for further validation and usability studies [166], [162]. Nevertheless, AR provides unique features that are suitable for the construction field. Indeed, positive results from BIM-based AR applications have been reported in increasing the efficiency of construction projects [176], engineering safety training [157], new ways to approach design [121], collaboration and decision making [153], as well as to support the progress of project schedules, and to supervise fieldwork [157].

Q5 What are the limitations of BIM-based AR, and are they being solved in recent research?

A5 The primary reported barriers were the lack of accuracy in the position of virtual objects and their marker locations, the high processing power needed to deliver a high-quality image, and the lack of connectivity in some construction sites.

Although seemingly easier to apply, marker-based AR systems face limitations as construction sites tend to be complex environments. In particular, markers must be placed carefully and remain visible at all times to provide a well-functioning application. Thus, markerless AR approaches tend to be a more practical alternative [153]. Additionally, AR still presents limitations regarding the presentation of construction-related information. Developments are required to improve visual occlusion, indoor GPS connection to correctly display digital objects, responsiveness in terms of frame rate, and user experience considering the size of the underlying BIM models [126].

AR interfaces may entail previous training sessions to overcome usability problems, as performance can be influenced by the degree of users' previous AR-related experience [153]. The relevance of user-centred approaches in line with technology-centred methods is highlighted by [164]. Indeed, considering usability challenges, the users' requirements and their experiences related to specific tasks are deemed paramount in the research for practical application of BIM-based AR interfaces [164], [154].

Q6 What are the main target groups?

A6 The main target groups verified in the articles were Construction Managers (Site and Resources Controllers, and Quality Controllers) with 26 occurrences; and Workers with 12. Also, Design Engineers (nine occurrences); Architects (eight occurrences); Owners (seven occurrences); and Facility Managers (six occurrences) were identified, although with minor prominence. Safety Managers were addressed in two publications, and Students were the target in one article.

Q7 How are these interfaces being assessed (e.g., qualitative, quantitative, comparative assessments, case studies, usability assessments)?

A7 Most systems are validated through case studies identified in 17 articles [31], [135], [164], [167], [168], [171], [176]–[178], [150], [151], [153], [154], [156]–[158], [160] of which four describe user tests [150], [31], [154], [168]. Assessing the interfaces' functioning through performance assessments and laboratory tests was verified in nine publications [151], [152], [155], [157], [159], [160], [165], [169], [176]. Moreover, eight studies state the collection of data through questionnaires [153], [154], [157], [160], [162], [165], [166], [168], and three present complementary data collected from interviews [155], [166], [167]. Additionally, AR systems' usability assessment is directly mentioned in four studies [153], [154], [160], [166].

Q8 What are the mainly researched BIM dimensions?

A8 From the screened articles, the most exploited BIM dimensions were 3D and 4D. While 3D was included in every screened paper, 7D was not directly mentioned in any article. Thus, the results indicate that the relationship between AR and BIM is still in development and concentrated in a limited range of BIM dimensions.

2.6 ON INFORMATION EXCHANGE AND INTEROPERABILITY

The present section sets forth a brief contextualisation of complementary concepts and notions of information exchange and interoperability concepts.

As discussed previously in section 2.4, the notion of Integrated Projects recognises a network of players who actively and instantly share data intrinsically connected to the developed tasks. Within BIM projects, data exchange must occur effectively and be aware of possible limitations that may hamper the process. Given the fragmented nature of the AECO sector [193], without an open and proprietary-neutral translator, information and value loss will take precedence along the project life-cycle (Figure 17). When information is passed to the next project phase without adequate interoperability, team members often need to revise the previous work resulting in a loss of value and time [194]. As such, a neutral resolution is necessary to ensure that BIM information is exchanged between parties without major information loss.

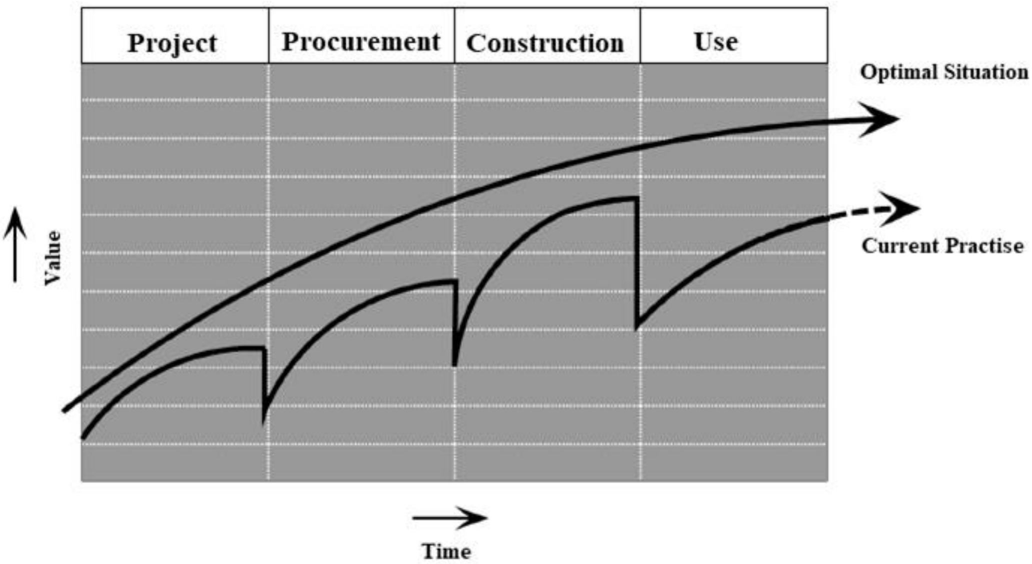

Figure 17 - Decrease in value along the project phases, adapted from [195].

The understanding of interoperability, as defined by Shen et al. [196], considers the ability to guarantee that heterogeneous systems (e.g., software and hardware) are able to communicate and interpret data generated by any of the parties. In this regard, International standards have been developed to guarantee interoperability between the stakeholders involved in the AECO sector. ISO 10303, Standard for the Exchange of Product Model Data (STEP) [197], provides the technology base for many of these standards [196]. The IFC specification - ISO 16739 [198]– is the main format towards interoperability between BIM tools [194].

2.6.1 Brief contextualisation on IFC

IFC was originally developed by the International Alliance for Interoperability (IAI), an alliance of organisations from the AECO sector, currently BuildingSMART alliance (since 2008) [199]. Although exclusively dedicated to the construction industry and related fields, the IFC has its origins in the ISO-STEP initiative [36]. With its first release in 1997, IFC is based on EXPRESS and more recently adapted to the Extensible Markup Language (XML) format (since 2001, ifcXML has been available [200]).

IFC2x marks the point where a methodology to convert IFC-EXPRESS to ifcXML schema was applied (see also ISO 10303-28:2007 [197] for further details concerning XML and EXPRESS data exchange).

Therefore, the ifcXML format presents an alternative to the STEP Physical File (SPF) representation [201]. Presently, IFC 4.1 stands as the latest and recommended version, while IFC data schema is specified in ISO 16739-1:2018 [198].

The IFC structure follows a hierarchical configuration assembled on objects and classes. For instance, proprieties are inherited from higher to lower-level classes.

Since its first release in 1997, IFC has embraced a series of revisions and updates, as exposed in Table 14.

Table 14 - Summary of IFC schema releases. Adapted from buildingSMART [202].

Date	**Identifier**	**Documentation**	**ISO Standard**	**Summary**
Upcoming	4.4. - dev	IFC4.4.0 development	Not started	In the early development phase. New additions will target tunnels.
Upcoming	4.3.1.0			
Currently under voting	4.3.0.1	IFC4.3. TC1	Under ISO Draft International Standard (DIS) voting	
2019	4.2.0.0	IFC4.2		
2018	4.1.0.0	IFC 4.1	-	Extension for civil infrastructure with alignment curves and solids.
2017	4.0.2.1	IFC4 ADD2 TC1	ISO 16739-1:2018	
2016	4.0.2.0	IFC 4 ADD2		
2015	4.0.1.0	IFC 4.0 ADD1		Addendum for optimised polylines and arcs.
2013	4.0.0.0	IFC 4.0	ISO 16739:2013	Platform improvements with NURBS geometry.
2007	2.3.0.1	IFC 2x3 TC1	ISO/PAS 16739:2005	Documentation expansion and fixes.
2005	2.3.0.0	IFC2x3		Quality improvement. of the previous release.
2004	2.2.1.0	IFC2X2 ADD1		Fix issues that came up during implementation.
2003	2.2.0.0	IFC2X2		Extensions for mechanical and electrical domains.
2001	2.1.1.0	IFC 2x ADD1		Fix issues that came up during implementation.
2000	2.1.0.0	IFC 2x		Stable platform.
1999	2.0.0.0	IFC 2.0		

Even though IFC has been updated throughout the years, the AECO sector is far too extensive and complex to map on a global scale [203]. To address this issue, custom property sets may be added to the IFC schema to suit particular domains through current BIM platforms. The entity IfcPropertySet defines the structure of attributes to be added, including the name, object(s) to be attached, and individual properties [204].

2.6.2 Information Delivery Manual

Each project stakeholder must be aware of the information requirements comprised in the exchange processes during the project life-cycle. The definition of a specific process and the related information demands is set in an Information Delivery Manual (IDM) [14]. As such, IDMs (ISO 29481-1:2016 [205]) set exchange requirements, thus performing as a reference for processes and data [206]. Additionally, Process Maps are included in IDMs to provide graphical representations of activities flow, representing the parties involved and the information stages (i.e., required, consumed and produced) within exchanges [207].

Pinheiro et al. [206] assert that IDMs are a standardised method for stakeholders that simultaneously define the information to be exchanged, who needs this information and at which stage. De Pinho [194] states that IDMs link processes to information demands, acting as references to the importance, the involved parties, the benefits and the reasons to support required information by BIM processes. As supported by Berard and Karlshoej [208], the IDM should provide datasets of building products and processes, regardless of the format. Additionally, the authors describe that IDMs may prove overly thorough in addressing building products or BIM objects. Hence, a balance must be attained to describe the processes as comprehensively as possible while keeping them general enough to suit the diversity of projects and organisation interactions.

An overview of the technical architecture of an IDM is presented in Figure 18, where the top layers comprise process definitions, descriptions as well as components related to industry practitioners. The middle layer regards data specifications. The last level is related to application software elements and comprises ICT analysts and programmers.

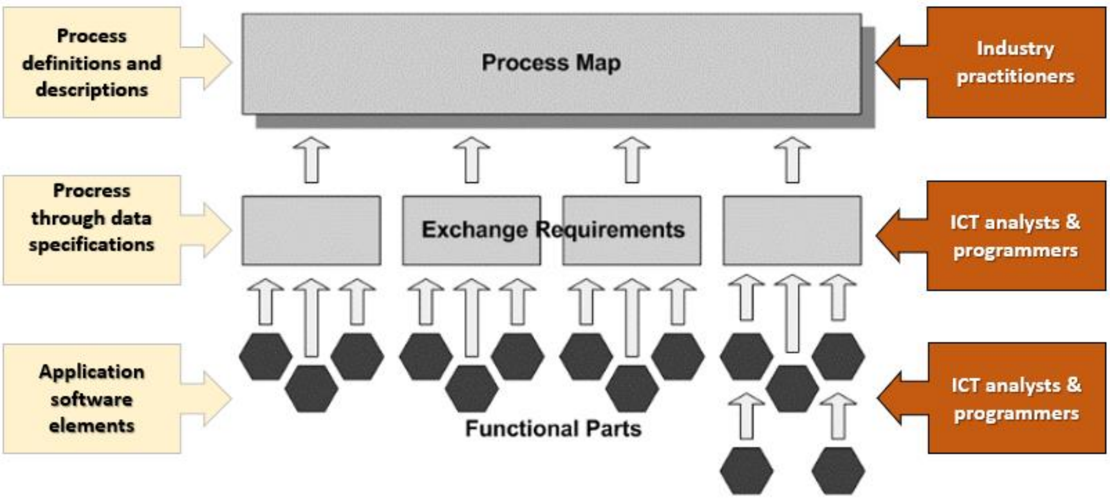

Figure 18 - Technical architecture of an IDM, adapted from [207].

2.6.3 Model View Definition

Specific business processes may not require all IFC entities. Therefore, Model View Definition (MVD) is applied to refine and select only the relevant subsets of information needed for a particular exchange.

MVD is a subset of the data schema and referenced data [198] to streamline information exchanges of particular tasks.

For instance, the Coordination View, based on the IFC2x3, and more recently, the Reference View and Design Transfer View of IFC4 Addendum 1, are MVDs developed and published by buildingSMART [206]. A comparison of the number of entities of IFC4 to other MVDs is presented in Figure 19Figure 19.

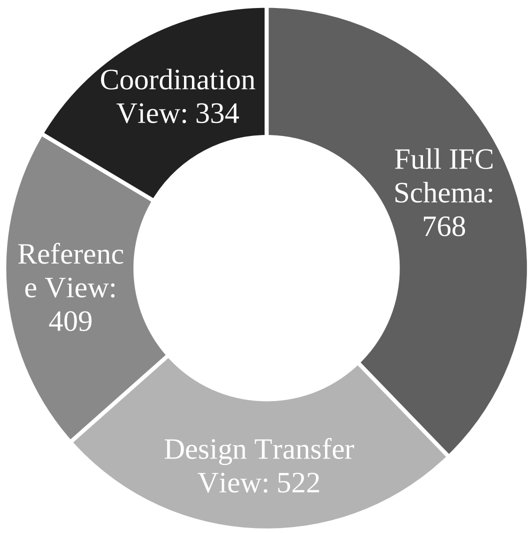

Figure 19 - Number of entities present in different MVDs compared to a full IFC Schema, adapted from [206].

Sacks et al. [14] emphasise that IFC is too wide-ranging and dense to correspond to the diverse demands of the parties involved. Indeed, a filtered view or a subset of the IFC schema is required to support tasks and exchanges [14], which is accomplished by the MVD. As a portion of the IFC schema, an MVD satisfies the exchange requirements defined in the IDM [206].

MVD applications may be found on initiatives such as HVACie (Heating, Ventilation and Air Conditioning - HVAC), SPARKie (electrical systems), LCie (facilitate systems integration and management); WSie (manage components, assemblies and systems related to water distribution and removal); COBie (Facility Management), among others [209].

2.6.4 Building Collaboration Format

The Building Collaboration Format (BCF) is an open standard that allows the exchange of information without the necessity of compiling the entire BIM model. The format was originally based on the XML schema (i.e., bcfXML) and was devised to support a lean workflow for the exchange of BIM-related segments of information (e.g., issues, requests) [210]. In detail, the BCF schema establishes a link to the IFC Globally Unique Identifier (GUID) of the elements, hence identifying the building object [193]. A particular aspect of the BCF format is that, even if a previous BIM model does not exist, the non-geometric information is still saved as BIM data to be applied in later stages of the project.

Berlo and Krijnen [193] describe that the initial BCF workflow was file-based and not centralised (e.g., e-mail based). Therefore, management, tracking of issues and revision were constrained, affecting the performance trace of products and suppliers. Currently, Web-based collaborative services are possible through BCF-Web service "bcfAPI", relying on Hypertext Transfer Protocol (HTTP) and JavaScript Object Notation (JSON) data formats [211].

2.6.5 On the definition of the degree of information (LOD, LOI, and LOIN)

Throughout the various phases of construction projects (e.g., design, procurement, construction and use), models tend to increase their complexity by storing cumulative amounts of information and higher levels of detail. Hence, BIM models may display different levels of refinement and complexity, complying with the demands of various actors throughout the stages of a project. Among other guidelines, American Institute of Architects (AIA) Document E202 [212] stands out for presenting a general guide to be used alongside contracts that has marked the development and applications of Level of Development (LOD) ever since. The guide establishes the LOD and defines six levels of incrementation (i.e., LOD 100, 200, 300, 350, 400 and 500) [14].

Different LOD may be required for greater reliability and monitoring of the information contained in the elements of the model. Therefore, the characteristics of the elements to be delivered by the different stakeholders may achieve clearer specifications and detail. Indeed, setting standard LOD may improve the quality of the communication towards the characteristics of the elements and simultaneously support contractual and normative basis such as the BIM Execution plan [14], [213].

Sacks et al. [14] allude to the importance of setting the appropriate degree of detail towards different stages and purposes within the project life-cycle. Yet, the authors ascertain that LOD are relevant as general guidelines that shall not excuse the use of more demanding descriptions such as MVDs.

Several entities and institutions have adopted their interpretation of LOD, therefore elaborating LOD guides (e.g., the LOD guide of Hong Kong, New York, United States Army Corps of Engineers *(*USACE)) [14]. However, consideration may be given to the fact that in the United Kingdom, the LOD concept has been detailed in two components: the Level of Modelling Detail and the Level Of Information. The first concentrates on developing the models' geometric aspects, while the second focuses on non-geometric information. Henceforth this study will address LOI according to the United Kingdom (UK) approach.

Also worth mentioning is the Level of Information Need (LOIN), introduced by ISO 19650-1:2018 [23] and further detailed in BS EN 17412-1:2020 [214]. This recent standard specifies the granularity and required information (i.e., alphanumeric and geometric, as well as additional documentation) to be exchanged by the actors throughout the phases of a construction project [215], [216]. Also, LOIN refrains from identifying specific levels [217] and requires that specific metadata be included instead [216]. Hence to perform a specific task, information exchange scenarios need the definition of a purpose (why), the actors involved (who), and milestones (when) [216], [217]. The LOIN standard advances over existing definitions (e.g., LOD) [216] and adds more clarity to the conflicting terminology used between the sector [215]. Furthermore, unlike the LOD, a LOIN may encompass multiple building elements and does not build upon previous LOIN occurrences [216].

2.6.6 Information Delivery Specification

IFC models' information and relationships may be validated against an Information Delivery Specification (IDS) comprising simple requirements [218], [219]. The .ids format is based on XML and contains a list of information specifications that BIM objects must comply with [218], [220].

Although still in development at the time of writing, this standard can be used to specify and exchange requirements through a streamlined approach by the client and be automatically validated by the modeller/user using compatible software tools. IDS aligns with EN 17412-1:2020 [214] perspective of “alphanumeric information” in the Level of Information Need [220] and includes specifications divided into three parts: description, applicability, and requirements. While descriptions are prone for humans to read, applicability and requirements are meant to be interpreted by software tools and are described using “Facets” [218]. Thereby, “Facets” are employed to specify entities’ information by resorting to “Facet Parameters” of different “Facet Types” (e.g., Entity, Attribute, Classification, Property, Material, and Parts) [218].

Current open-source toolkits such as IfcOpenshell [189] are compatible with the IDS standard and allow user-defined specifications [221]. Figure 20 illustrates the structure of an IDS.

```
<?xml version="1.0" encoding="UTF-8"?>
<!-- IDS (INFORMATION DELIVERY SPECIFICATION) CREATED USING IFCOPENSHELL -->
<ids xmlns="http://standards.buildingsmart.org/IDS" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    <specification name="Fire requirement specification (IfcWall)" necessity="required">
        <applicability>
            <entity>
                <name>
                    <simpleValue>IfcWall</simpleValue>
                </name>
                <predefinedtype>
                    <simpleValue>CLADDING</simpleValue>
                </predefinedtype>
            </entity>
        </applicability>
        <requirements>
            <material location="any">
                <value>
                    <simpleValue>TIMBER</simpleValue>
                </value>
            </material>
            <property location="any">
                <propertyset>
                    <simpleValue>Structural</simpleValue>
                </propertyset>
                <name>
                    <simpleValue>Strength class</simpleValue>
                </name>
                <value>
                    <simpleValue>C30</simpleValue>
                </value>
            </property>
        </requirements>
    </specification>
    <info>
        <date>2022-10-29</date>
    </info>
</ids>
```

Figure 20 - Example of an IDS specification, based on [220].

2.7 BIM AND SEMANTIC ENRICHMENT

Several authors highlight current hurdles related to interoperability amongst BIM practices concerning information sharing and management. For instance, the IFC schema [198], the most generally used standard for model exchange in the AECO sector [222], still presents potential redundancies of information [223], [224]. Constraints are also identified regarding the formalisation of domain-specific information such as context-reliant and exclusive data (e.g., built heritage representation) [225], despite IFC's broad scope.

Regardless of the relevance of the IFC format as the main standard for exchanging and interpreting geometric and topological information among BIM tools, several methods and approaches aim to enrich BIM models using information that is often not fully mapped by standardised schemas. Indeed, some initiatives are dedicated to devise and enhance automatic computational methods to overcome consistent inefficiencies in the integration of multiple sources of information, improve laborious manual modelling update efforts [226], as well as methods to add and infer missing information combining multidisciplinary knowledge as BIM is noticeably implicated in a wider net of technologies and research areas (e.g., Computational Engineering [227], [228], Computational Design [229], Computer Graphics and Informatics [230], [231]). Among the various applications of BIM, the use of semantics stemming from different sources and databases, as well as domain rule sets, provide means to enrich and handle the information of existing models [226]. In this regard, SE approaches can automate the process of obtaining and inferring missing information required by a receiving application [232]. SE may be achieved through different computational approaches to increase the LOI of a BIM model and through developments aimed at extending the structure and schema of data [233].

The present thesis adopts the notion of SE described by Sacks et al. [14], defining SE as a process through which new information is automatically or semiautomatically added to a model through particular techniques that may infer new facts, such as processing rules and machine learning (see also Belsky, Sacks, and Brilakis [223] and Bloch and Sacks [232]).

Xu et al. [234] report that semantic information included in BIM models can be subdivided into two subcategories:

a) semantic information on individual elements; and

b) semantic information on the relationships between components (i.e., information regarding dependencies between elements, topological information, among others).

Thus, for the first subcategory, semantic information could be organised in:

a.i) Geometric characteristics (e.g., position, shape, texture);

a.ii) Non-geometric characteristics (e.g., function, material specifications).

This section presents a semi-systematic literature review [235] on BIM and SE applications to disclose the developments in this research field achieved during the last decade. In particular, the review concerns BIM-based approaches aiming at increasing the semantic information of individual elements, particularly at the non-geometric level, as well as the relationships between components – aforementioned a.ii) and b) subcategories.

While considered a relatively emergent area of research and given the limited bibliography on the subject, as mentioned by Bloch and Sacks [232], there is the need to realise:

i) What are the main developments and approaches regarding BIM and SE?
ii) What are the current limitations of such methods?
iii) What are the BIM uses and application domains for SE?
iv) What are the future research recommendations?

To this end, existing research published in peer-reviewed journals was screened and thoroughly analysed to provide an extensive overview of the main approaches, application domains, prevailing authors, as well as current limitations and expected research developments regarding SE and BIM.

The research methodology follows the general principles of a semi-systematic approach [235] and is based on past review studies [236], aiming at high-quality research papers focused on BIM and SE. The search was operated through two leading platforms for the dissemination of peer-reviewed scientific publications, respectively, the Scopus database and WebOfScience (All sources).

Keyword combinations between BIM and Semantic Enrichment were established to refine the paper acquisition: "BIM" and "Semantic Enrichment"; "Building Information Modelling" and "Semantic

Enrichment, and "Building Information Modeling" and "Semantic Enrichment". As criteria for filtering publications, research was restricted exclusively to scientific peer-reviewed articles published in international journals and written in English.

In the first search stage, 55 papers were retrieved from the Scopus database, and 30 documents were found through the WebOfScience platform. However, after applying the filtering criteria, checking for the repetition of records, eliminating irrelevant articles, and then reading abstracts to confirm the scope of publications when deemed unclear, a total of nine initial publications were found to meet the inclusion criteria for this study. These articles, although few, established a secure starting point based on high-quality research complying strictly with the inclusion criteria. This ensured that the review could then be expanded into further procedures on a sound basis. Further screening was performed on the references of articles that conformed with the inclusion criteria, resulting in 21 additional publications. The final review considers a total of 30 articles published in peer-reviewed journals written in English between 2010 and 2020. Figure 21 summarises the overall screening process and research procedure.

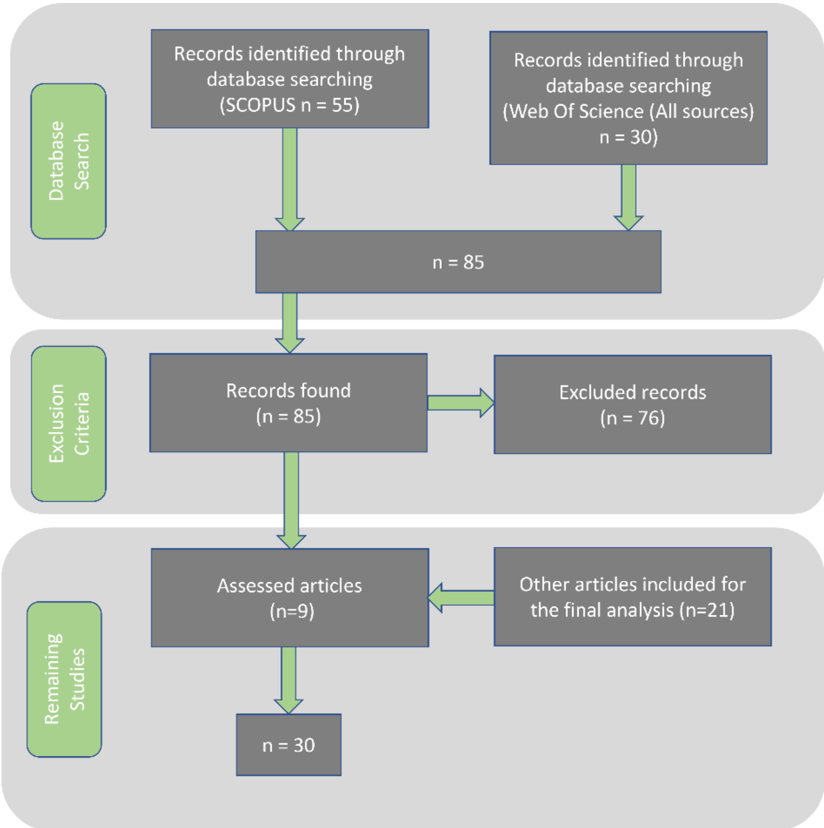

Figure 21 - Research procedure, adapted from [237].

2.7.1 Screened studies contextualisation

This section focuses on the contextualisation of the screened articles to convey an overall perception of the research. Thus, the chapter focuses on the frequency of publication over the last decade, geographical dispersion given the first author's institution, most cited papers, prevailing journals, and keyword combinations.

From the included articles, an increase is noted in the number of published papers from 2014, with previous years registering two publications or fewer.

Regarding the geographical distribution of the studies (Figure 22), most were developed in the United States (first authors' institutions) with seven publications, followed by Israel, Germany, and France with three publications each.

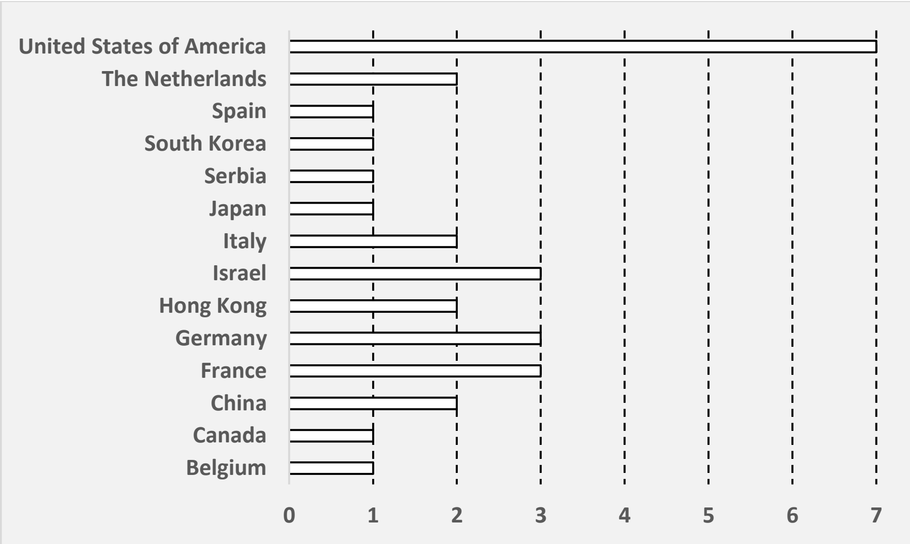

Figure 22 - Number of publications associated with the country of the first author's institution, adapted from [237].

The five most-cited publications in the last decade, at the time of writing, were Zhiliang et al. [238] with 76 citations, and Karan and Irizarry [239] with 64 citations, both published in Automation and Construction; followed by Mignard and Nicolle [240], 61 citations, in Computers in Industry; Mazairac and Beetz [241], 60 citations, in Advanced Engineering Informatics, and Belsky, Sacks, and Brilakis [223], 57 citations, in Computer-Aided Civil and Infrastructure Engineering.

Most publications originated from Automation in Construction (9 publications); Journal of Computing in Civil Engineering with six publications; followed by Advanced Engineering Informatics, and Computer-Aided Civil and Infrastructure Engineering, presenting three publications, respectively. No other journals published more than two articles that met the criteria of this review. This information is organised and detailed in Table 15.

As depicted in Figure 23 (on the left), the most occurring keywords are “Building Information Modeling” (21 occurrences), followed by “Semantic Enrichment”, “Ontology”, “Linked Data”, and “Interoperability”, with four occurrences, respectively. “Semantic web”, and “Industry Foundation Classes (IFC)” regard three occurrences each. Furthermore, a strong link is verified between “BIM”, and computational approaches such as “Semantic Enrichment”, “Semantic Interoperability”, and “Semantic Web Technology”, as depicted in 2 of the 6 clusters in Figure 23 (on the right).

Table 15 - Details of the screened papers.

Journal	Title	Authors	Year	Citations	Country of the first author's institution
Advanced Engineering Informatics	An approach to distributed building modeling on the basis of versions and changes	Christian Koch Berthold Firmenich	2011	22	Germany
	BIMQL – An open query language for building information models	Wiet Mazairac Jakob Beetz	2013	60	The Netherlands
	Formalized knowledge of construction sequencing for visual monitoring of work-in-progress via incomplete point clouds and low-LoD 4D BIMs	Kevin K. Han David Cline Mani Golparvar-Fard	2015	31	United States
Automation in Construction	Application and extension of the IFC standard in construction cost estimating for tendering in China	Ma Zhiliang Wei Zhenhua Song Wu Lou Zhe	2011	76	China
	Development of space database for automated building design review systems	Jin-Kook Lee Jaemin Lee Yeon-suk Jeong Hugo Sheward Paola Sanguinetti Sherif Abdelmohsen Charles M. Eastman	2012	50	United States
	Connecting building component catalogues with BIM models using semantic technologies: an application for precast concrete components	G. Costa L. Madrazo	2015	39	Spain
	Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services	Ebrahim P. Karan Javier Irizarry	2015	64	United States
	A linked data system framework for sharing construction defect information using ontologies and BIM environments	Do-Yeop Lee Hung-lin Chi JunWang Xiangyu Wang Chan-Sik Park	2016	30	South Korea
	Comparing machine learning and rule-based inferencing for semantic enrichment of BIM models	Tanya Bloch Rafael Sacks	2018	17	Israel
	BIM semantic-enrichment for built heritage representation	Davide Simeone Stefano Cursi Marta Acierno	2019	14	Italy
	Bridge damage: Detection, IFC-based semantic enrichment and visualization	Dušan Isailović Vladeta Stojanovic Matthias Trapp Rico Richter Rade Hajdin Jürgen Döllner	2020	1	Serbia

	Scan-to-graph: Semantic enrichment of existing building geometry	Jeroen Werbrouck Pieter Pauwels Mathias Bonduel Jakob Beetz Willem Bekers	2020	0	Belgium
Building and Environment	Integrating 4D thermal information with BIM for building envelope thermal performance analysis and thermal comfort evaluation in naturally ventilated environments	Worawan Natephra Ali Motamedi Nobuyoshi Yabuki Tomohiro Fukuda	2017	20	Japan
	Ontology-based framework for building environmental monitoring and compliance checking under BIM environment	Botao Zhong, Chen Gan, Hanbin Luo, Xuejiao Xing	2018	13	China
Computer-Aided Civil and Infrastructure Engineering	Multi-Scale Geometric-Semantic Modeling of Shield Tunnels for GIS and BIM Applications	A. Borrmann T.H. Kolbe A. Donaubauer H. Steuer J.R. Jubierre M. Flurl	2015	50	Germany
	Semantic Enrichment for Building Information Modeling	Michael Belsky Rafael Sacks Ioannis Brilakis	2016	57	Israel
	Automatic Generation of Semantically Rich As-Built Building Information Models Using 2D Images: A Derivative-Free Optimization Approach	Fan Xue Weisheng Lu Ke Chen	2018	11	Hong Kong
Journal of Computing in Civil Engineering	BIM and GIS Integration and Interoperability Based on Semantic Web Technology	Ebrahim P. Karan Javier Irizarry John Haymaker	2015	37	USA
	Extending Building Information Models Semiautomatically Using Semantic Natural Language Processing Techniques	Jiansong Zhang Nora M. El-Gohary	2016	12	USA
	Automated Schedule and Progress Updating of IFC-Based 4D BIMs	Hesam Hamledari Brenda McCabe Shakiba Davari Arash Shahi	2017	24	Canada
	Semantic Enrichment for Building Information Modeling Procedure for Compiling Inference Rules and Operators for Complex Geometry	Rafael Sacks Ling Ma Raz Yosef Andre Borrmann Simon Daum Uri Kattel	2017	26	Israel
	IFC-Based Development of As-Built and As-Is BIMs Using Construction and Facility	Hesam Hamledari Ehsan Rezazadeh Azar Brenda McCabe	2018	14	USA

	Inspection Data: Site-to-BIM Data Transfer Automation				
	From Semantic Segmentation to Semantic Registration: Derivative-Free Optimization-Based Approach for Automatic Generation of Semantically Rich As-Built Building Information Models from 3D Point Clouds	Fan Xue Weisheng Lu Ke Chen Anna Zetkulic	2019	5	Hong Kong
Computers in Industry	Merging BIM and GIS using ontologies application to urban facility management in ACTIVe3D	Clement Mignard Christophe Nicolle	2014	61	France
Construction Innovation	Generating IFC models from heterogeneous data using semantic web	Ebrahim Karan Javier Irizarry John Haymaker	2015	0	United States
Graphical Models	Service-oriented semantic enrichment of indoor point clouds using octree-based multiview classification	Vladeta Stojanovic Matthias Trapp Rico Richter Jürgen Döllner	2019	2	Germany
Journal of Cultural Heritage	Knowledge-based data enrichment for HBIM: Exploring high-quality models using the semantic-web	Ramona Quattrini, Roberto Pierdicca Christian Morbidoni	2017	31	Italy
Personal and Ubiquitous Computing	Semantic enrichment of spatio-temporal trajectories for worker safety on construction sites	Muhammad Arslan Christophe Cruz Dominique Ginhac	2019	6	France
Procedia Environmental Sciences	A web-platform for linking IFC to external information during the entire lifecycle of a building	Marc Dankers Floris van Geel Nicole M. Segers	2014	0	The Netherlands
Safety Science	Visualizing intrusions in dynamic building environments for worker safety	Muhammad Arslan Christophe Cruz, Dominique Ginhac	2019	4	France

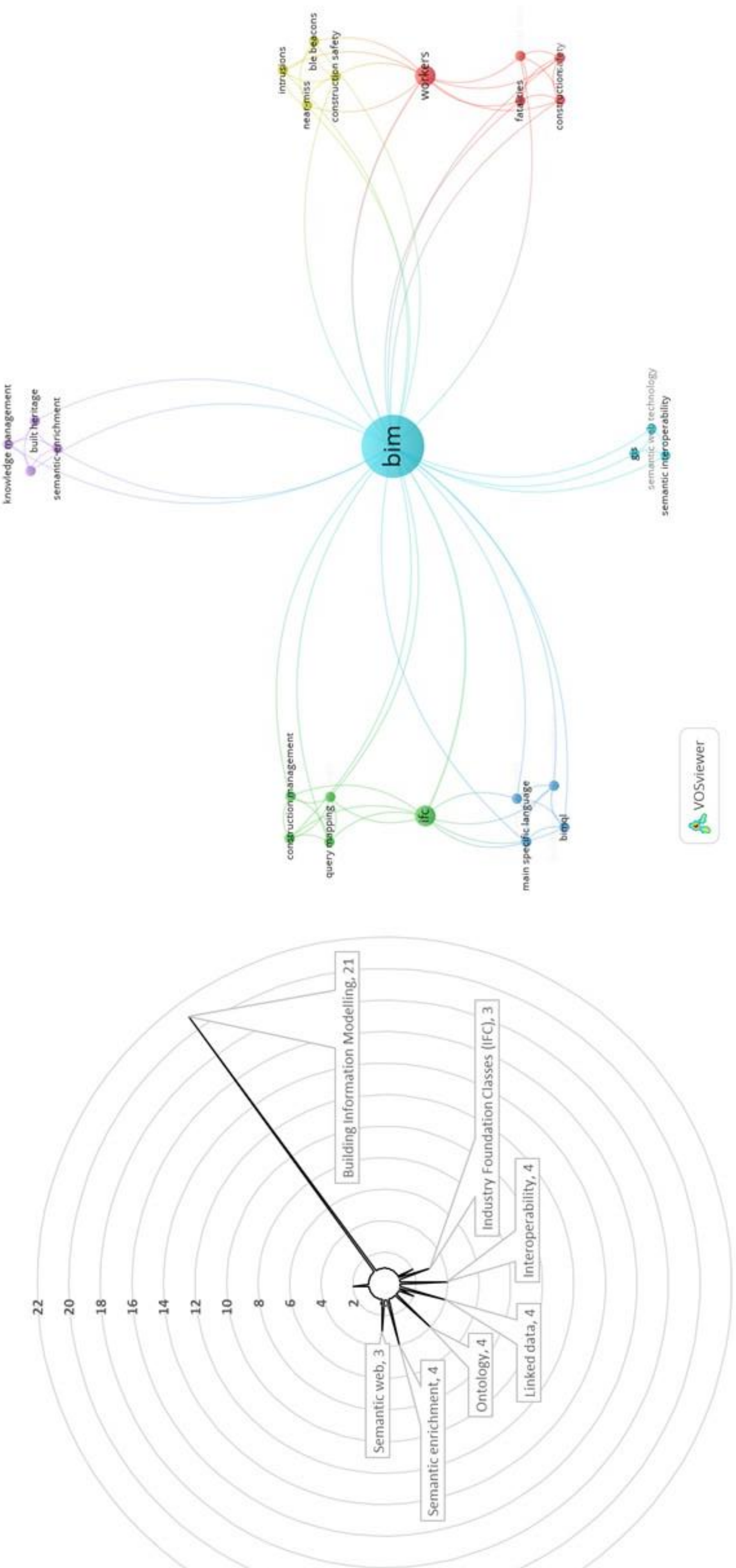

Figure 23 - Keyword incidence (on the left) and co-occurrence (on the right), adapted from [237].

2.7.2 Analysis of the screened papers: applied methods, verified limitations, and corresponding BIM uses

This section describes the methods presented in each article included in the review. The analysis is guided by categorising each publication according to the use of the BIM methodology at a given project stage. Thus, articles will be grouped according to the primary BIM Use [118] as classified by the authors of this study, followed by a description of the computational methods, algorithms and approaches used for SE as well as current research limitations.

Overall, nine main BIM Uses were identified among the included papers. In particular, "Capture Existing Conditions" was the most verified BIM Use (nine articles), followed by "Validate Code Compliance" (five articles), "Review Design Model", and "Author 4D Model" (three articles, respectively). Finally, "Author Design", " Analyse Site Selection Criteria", " Author Construction Site Logistics Model", "Coordinate Design Model(s)", and "Analyse Energy Performance" registered two occurrences or fewer.

Capture Existing Conditions

Focusing on the as-is state of a building and the absence of interpreted content and semantics in a point cloud, Stojanovic et al. [242] developed an approach based on deep learning algorithms to facilitate the automation of semantic content. The information otherwise visually interpreted by a user and lacking associated semantics is now reviewed and validated through classification algorithms (i.e., image classification was achieved using a Convolutional Neural Network (CNN), Inception v3, from TensorFlow). Then, the continuous increment of semantic information is added through a web interface to clusters of a point cloud. The interface has been evaluated, and the authors mention its potential for greater participation in supporting the decision-making process by the stakeholders involved in the construction projects, namely during the facility management phase. As to the limitations of the proposed approach, the authors emphasise the lack of accuracy when trying to classify objects presenting similar surface properties (i.e., Red, Green, and Blue (RGB) colour, point density, or shape). Furthermore, specific furniture styles would require retraining the algorithm with dedicated datasets (e.g., images, point clouds).

Xue, Lu, and Chen [234] propose a method to identify BIM objects through a constrained optimisation approach. In detail, measurement data is segmented, and the similarity between the features of the as-built conditions and the BIM objects is considered. COMBING, an open-source library "constrained optimisation-based BIM generator", is presented by the authors as an open-source library to conduct similarity analysis between the parameters (e.g., scale, rotation, position, topology). As such, semantically enriched BIM models are automatically generated according to the IFC standard. The authors highlight that the main performance bottleneck is posed by SketchUp, which consumes the majority of the processing time in manipulation tasks and 3D to 2D projections.

A contribution to the previous study is presented by Xue et al. [243], describing the development of an as-built BIM generator plugin, COMBING-Revit. The approach uses point cloud data to map building elements to corresponding Revit families through an iterative procedure based on a constrained optimisation problem which tries to minimise the error between the point cloud and the resulting BIM model. The presented approach differentiates from machine-learning methods since it does not require training. Results from a case study mention the use of a Google Tango-compatible device to generate the point cloud and download the candidate Revit families. The approach shows encouraging outcomes in terms of geometric accuracy and time performance (cf. [243]), as well as matching semantic properties into the detected objects (e.g., topological relations, materials, assembly code, and other producer-related information).

Nevertheless, the proposed approach is dependent on external data, such as geometric information and semantics. Furthermore, instance parameters still lack precision (e.g., the accurate height of an armrest). Information such as colour and texture needs further developments to be detected.

In a study by Simeone, Cursi, and Acierno [225], family templates and family types were developed with specific parameters for Historic Building Information Modelling (HBIM) to integrate and systematise the knowledge devised through information ontologies. The research intended to improve the representation quality in a BIM model addressing requirements related to the building heritage and conservation processes. The authors' approach comprises four main components: i) BIM environment; ii) Knowledge base (ontology-based system); iii) Semantic Web Rule Language (SWRL) component to address reasoning in the knowledge base; iv) "BIM Semantic Bridge" to establish a relation between the BIM data and the knowledge base. The comprehensive approach is of particular contribution to the building conservation and architectural history domains, as it regards four fields of knowledge: Artefact, Lifecycle, Built Heritage Conservation Process, and Actors. These domains are set using semantic networks comprising entities, properties, and relationships. Through SE, building elements that may hold a different purpose than their initial function can be thoroughly defined; for instance, the case of a column with the initial structural role now embedded in a structural wall [225]. In this way, the articulation between the classes defined in the ontology and the BIM families and types is required since the representation in the databases (BIM and knowledge base) is distinct. Therefore, there was a need to create a "BIM Semantic Bridge" to translate the two environments into one, thus creating correspondences between the entities represented in both. As to current limitations, the IFC standard is depicted as unsuitable for the uniqueness of artefacts related to building heritage domains resulting in a lack of accuracy and consistency. Additionally, gaps associated with the representation of more specific and context-related information to enhance the awareness of the actors' conservation assessment and choices are highlighted [225] as one of the barriers of BIM-based modelled information and semantics.

A web application was developed to explore monumental and historical building data, providing easier model querying by assessing both the model data and 3D geometry [244]. The authors describe a semantic-web approach that includes an ontology using the Ontology Web Language (OWL). Furthermore, a BIM model was devised using Revit and added shared parameters following the domain ontology properties. Finally, the model was exported to the IFC format and converted to Resource Data Framework (RDF) data within a knowledge graph structure (Aalto University and Ghent University conversion tool – IFC to ifcOWL) and further queried using Semantic-web query language (SPARQL Protocol and RDF Query Language - SPARQL). Besides the possibility of different building data to coexist in the same graph structure, semantic structures allow querying data by its meaning as well as overcome some of the IFC limitations by enabling the possibility of querying multiple models simultaneously [244].

The IFC schema limits the building element entities it can contain, thus restricting the classification of more complex and non-contemporary buildings [245]. On the other hand, BIM tools are better suited to the design of new buildings than to the maintenance of existing ones. Therefore, Werbrouck et al. [245] developed an approach to extend and incorporate information from other databases into current classification schemas. The scan-to-graph approach, based on the concepts of Linked Data technologies, aims to support the current scan-to-BIM processes to boost information interoperability with other disciplines involved in reconstruction processes. The authors describe a plugin for the Rhinoceros software, which allows the creation of RDF graphs. The plugin supports the inclusion of topological and geospatial information, import of point clouds, enables SE, and possesses the option to use SPARQL. The SE process comprises the topology information, element classification, and metadata related to occlusions and adding remarks. In contrast, enabling the extension and classification of more complex or unique elements may lead to creating custom classes without ensuring that those same entities may exist in another taxonomy [245]. As such, the option to promptly check for available entities is identified by the authors as a necessary measure.

Sacks et al. [233] developed an improved version of the SeeBIM tool [223] to increase the semantic level of BIM models. Initially, several point clouds were pre-processed for a later manually modelled bridge in a BIM authoring tool. These models were prepared and exported to the Coordination View (IFC) without any semantic information regarding the specific case of the bridge components. This information would then be added to the IFC using a SE process involving a set of inference rules and using a rule processing engine through a cyclic process that ends only when there is no additional information that can be inferred. Results show that for a bridge with 333 elements of 10 different types, a classification with 100% accuracy was achieved. The process involving rule sets results in the identification of all possible objects. However, errors in the geometrical model (input data) may invalidate some rules. Thus, to improve the classification outcome, redundancy in the number of rule sets may be beneficial.

The research conducted by Isailović et al. [246] reports an approach dedicated to the SE of bridge models, especially focused on information related to damage assessment. Apart from the process of geometric reconstruction of detected damage from point clouds, the approach allows the enrichment of semantic information related to damage data, such as type, severity, and extent. Furthermore, the method complies with the IFC schema as well as the Swiss Federal Roads Authority Bridge Management System (BMS), KUBA. In particular, the authors used IFCEngine [247], a C++ tool for managing STEP files. The authors describe the novelty of their approach as a dedicated and straightforward method focused on bridge damage severity assessment able to produce an as-is IFC model. However, after the enrichment process, the IFC model file size increased noticeably due to the amount of added data. The proposed process is described as time-consuming when compared with more traditional approaches; however, it is mostly achieved by automated processes. Finally, the system is presented as a web-based prototype.

A novel approach targeting as-is and as-built BIM representation presented by Hamledari, Azar, and McCabe [226] was driven by current barriers of inefficient data integration from site to BIM models, laborious manual modelling update effort, as well as lack of interoperability and data defective model update traceability. The authors describe a method based on Python and the IfcOpenShell open-source library that outputs updated IFC-based models with entities and properties related to on-site element inspections. Additionally, the approach is described as "independent" of the data source. In detail, data related to on-site observations, such as the responsible organisation or person for the inspection processes, design inaccuracies, affected elements, and images or notes, are linked to the correspondent elements in the BIM environment. The final IFC-based BIM model is also updated with colour schemas and supplemented with updated report documentation. The authors also refer to the limitation of having inconsistencies between detailed inspection reports and elements modelled with a low Level of Detail (LoD). This difference in detail may lead to data being added to a single element instead of the comprised building components, thus missing precision and reliability.

Validate Code Compliance

Various types of information need to be combined and shared among the different actors to meet the requirements of building codes, rule checks, and design conditions. In fact, in the AECO sector, the predominance of heterogeneous information causes interoperability issues between data formats [248]. Therefore, Zhong et al. [248] present an approach that aims at bridging gaps in the scope of semantic interoperability. In detail, a framework for building environmental monitoring and code compliance is presented that starts by collecting recorded information in several formats (e.g., text files, GIS, BIM, among others). Afterwards, the information is described through specific ontologies; and then analysed by reasoning engines and rule containers. Finally, the information is represented as RDF graphs and prone to semantic queries through SPARQL. The authors detail that the building knowledge domain was developed based on the ifcOWL ontology through Protégé 5.1. As for the BIM information, the necessary parameters were added to the model, exported to a text file, and later converted to RDF. Concerning the limitations of the proposed method, although semantic web technologies enable the representation of information using the same language, developing the ontologies is reported as a time-consuming process [248]. Additionally, the authors mention that their research assumes that all the required semantic information is included in the BIM models, which may not always occur in current practice.

Mazairac and Beetz [241] introduce a framework for a query language, BIMQL, that distinguishes itself from previous initiatives for being open and a domain-specific language (DSL), enabling non-technical users to be able to query BIM models. Moreover, the framework was devised as a plugin extending the resources of the bimserver.org platform. Through BIMQL, end-users may query models to find building elements (i.e., relations among IFC entities) complying with specific criteria or code requirements, as well as proceed with operations to modify the properties of certain elements. Future developments are envisioned to include higher conceptual levels to the query variables, integrate frequently used queries or MVDs such as mvdXML templates, as well as the option to request data from multiple sources/repositories to complete composite queries.

Also targeting regulatory concepts and automated compliance checking, a method for extending the IFC schema is presented in a study by Zhang and El-Gohary [249]. The approach uses both semantic natural language approaches (i.e., Porter Stemmer algorithm [250], hypernymy, hyponymy, and synonymy relations through WordNet [251]) and machine learning algorithms (i.e., k-Nearest Neighbour (k-NN), Support Vector Machines (SVM), Decision Tree (DT), and Naïve Bayes (NB)) to parse regulatory documentation using part-of-speech (POS) patterns and pattern-matching-based rules, to search for the most similar and matching IFC entities (versionIFC2X3_TC1). Although tests were conducted on limited chapters of the International Building Code (IBC) and only unigram (name with one term) matching was employed, encouraging results were obtained from the analysis of the IBC documentation concerning concept extraction, IFC concept selection, and relationship categorisation.

To comply with the Chinese standard National Unified Basic Quota of Construction Works (Chinese standard GJD-101-95), which includes the requirements for valuation of construction works (i.e., quantity calculation, units of measurement in cost estimation, division items, among many others), the research developed by Zhiliang et al. [238] establishes necessary IFC entities and reports the compatibility issues found in the process of meeting the Chinese standard requirements for information representation. Overall, 104 IFC entities were developed using IFCPropertySet class. However, the authors emphasise that the custom properties related to temporary products and division-items information were not identified by supporting IFC software, increasing the need to extend the IFC schema to streamline Chinese data exchange requirements.

Dankers, van Geel, and Segers [222] developed a web platform for ubiquitous use among the various types of users to access a wider range of information than that contained in BIM models without necessarily having to possess software licenses or CAD technical knowledge. The authors also mention that the mapping of IFC entities with a national object classification library was tested, albeit with little success, which would allow applications such as automatic cost estimation. In detail, the web interface is developed based on the BIMserver platform (see also Beetz et al. [252]) and consists of software as a service approach. It connects BIM objects to other metadata layers maintaining an IFC structure. The Drupal platform was used for content management to connect and map BIM elements and other complex datasets. The GUID of the IFC elements is used to connect these objects to the Drupal-based information management system. The system also allows adding various types of information to the mapped objects such as figures, charts, calculations, diagrams, among others. Additionally, whenever an entity is updated on the BIMserver, it is automatically updated on the proposed BMS. Although an automatic mapping of IFC entities to a Dutch standard classification system for cost estimation, NLSfB [253] was predicted, it was not successfully achieved given the limitations of IFC properties that did not allow for correct mapping of elements against position, construction system and function requirements.

Review Design Model(s)

Belsky, Sacks, and Brilakis [223] devised a prototype application, SeeBIM, that parses IFC models and analyses the relation amongst the geometric entities and their attribute values to infer new data about the model. The system is based on an IFC Engine and uses a BIM model exported according to IFC CV 2.0. specifications as input. In particular, SeeBIM uses forward chaining to provide new information regarding precast elements determined from the initial IFC model (e.g., objects, values, and topological relationships among them). Additionally, the authors devised a web interface to enable AECO professionals, even without programming skills, to be able to write rules so the model could be processed by an inference engine.

The research conducted by Bloch and Sacks describes the application of artificial intelligence algorithms to the classification of rooms (i.e., to their space function) while comparing their applicability to rule-inferencing approaches [232]. Due to the laborious job of having to input the necessary information so that a commercial software tool may detect and classify a given space, the authors propose an alternative based on artificial intelligence to streamline the process. As such, the use of machine learning algorithms is compared to other suitable approaches (i.e., rule-based inferencing) to assess the decisive features that determine their feasibility. Artificial Neural Networks (ANN) were employed based on the AZURE ML platform. While the results from the machine-learning classification algorithms observed a superior number of classified spaces, the credibility of the results should be verified due to the inductive reasoning nature of such approaches [232]. Moreover, the authors suggest that machine-learning approaches are subject to the condition of the chosen features and the size of the dataset.

Lee et al. [254] report the development of a spatial database and master table to map and standardise building classifications and names of building spaces, namely the United States (US) courthouse, which holds specific spatial semantics. Computer systems may use this specific spatial information to proceed with automatic design review checks [254]. The research addresses the problem in labelling space considering current hurdles of the industry, such as taxonomy systematisation, multiple space classification, space indexation, lexical issues related to abbreviations, ambiguities, among others. Indeed, the same space may have several designations, making it difficult for third-party applications to analyse. Explicitly, for certain domains, there is a very restricted semantic classification, which might be obvious for an expert user to detect manually; however, it will not be as easy to interpret when automatically processed by a computer [254]. In this sense, the authors have developed a master name table to map the different and possible designations in terms of spatial semantics so that space names and spatial properties can be automatically identified, even for specific building types, and imported into a BIM model. The proposed framework comprises a space database assembly using Solibri Model Checker, including the name designations and necessary spatial information. Secondly, the database is connected to a master name table with standard designations intended to be linked with spatial properties to be used in validation software tools. The framework allows BIM models to be enriched with name classifications and related spatial data, and results confirm (from the pre-processing module) that the approach successfully recognises the model spatial objects.

Author 4D Model

One of the current challenges in the AECO industry is the integration of captured data from the construction site to the BIM model (e.g., progress tracking data) [255]. In this regard, Hamledari et al. [256] present a method to update construction tasks and schedules automatically in BIM models. Irrespective of the input data format for detecting progress information, the proposed approach, BIM Automated Updating of Schedules (BAUS), updates the 4D BIM using the IFC format. Moreover, independently of the number of building elements and objects to be updated and the software used to devise the 4D BIM, BAUS is able to modify and extend the existing IFC file with new entities. The authors report using Python 2.7 and the open-source library IfcOpenShell to develop their method. Additionally, reported results show that the output IFC model, compared to the same manual updates of the BIM model, achieves superior file size efficiency. However, the use of BAUS to update highly detailed schedules is still prone to future developments as the dependency of some sub-tasks on the parent task, their constraints, sequence, and volume may require an expert's view.

To support the lack of information and details in visual detection and monitoring systems, Han, Cline, and Golparvar-Fard [257] report their approach to assisting construction sequencing assessment. In detail, to infer the construction sequence and progress stage, the authors formulated an ontology to map the relations between construction objects and their sequence rationale. The research emphasises scenarios of lack of visibility, occluded objects, incomplete Work-Breakdown-Structure (WBS) in construction schedules, or low Level of Development. By identifying the relations among building elements through the ontology, the methods intend to enrich the status of 4D BIM models. Although proposed case studies were merely hypothetical, results indicate that most scenarios to validate the ontology were acceptable. Furthermore, the authors refer that including quality checks regarding building components would be a significant direction for future developments.

To overcome the limitations of the use of BIM information beyond EXPRESS-compatible tools, Karan, Irizarry, and Haymaker [258] developed an approach that combines both building and geospatial semantics. The research conducted by the authors reports on a data framework that enables information share between BIM and GIS software [258]. BIM information (IFC format) is translated into an ontology describing its relationships and properties. On the other hand, the authors make use of existing GIS ontologies so that the result will be a mapping between IFC entities and GIS belonging to both ontologies into a semantic web format. Afterwards, information may be queried using SPARQL so that results may be loaded into a BIM authoring tool using the ifcXML format or a GIS software in comma-separated values (CSV) format. However, due to the differences in granularity in the data structure on both platforms, only part of the information could be conveyed and retrieved (query process). Nevertheless, results from the application on a case study of Construction supply chain management (CSCM) report that 40% of the semantics are retrieved from a two-way exchange, which overtakes "state-of-the-art tools" [258].

Author Design

Semantic Web technologies are considered effective in dealing with and combining information from varied ecosystems [259]. For instance, the development of ifcOWL [260] represents a format that enables IFC data to be shared across the web and adds the advantage of extracting partial information from SPARQL queries. Through the OWL specification, heterogeneous information and data formats may be integrated and formalised so that metadata can be interpreted by machines [259]. An example of the application of Semantic Web technologies to the design authoring domain can be found in a study by Costa and Madrazo [259]. The authors mention the development of a web catalogue interconnecting scatter and diverse information related to building components whose features can be elicited through SPARQL query language. As posed by the authors, ontologies act as agents or intermediaries between the queries and the sources of information. Therefore, an ontology was developed for the BAUKOM catalogue of prefabricated concrete components so that users may query a particular product and enrich a BIM model with it. Using the Unique Resource Identifier (URI), building components can be recognised on the Web and further associated to a graph structure of linked data (e.g., RDF graph). A Revit plug-in was devised to enable access to a certain building component of choice and the possible components that can be connected with it, thus streamlining otherwise cumbersome manual work [259].

Information exchange formats, such as IFC, represent intermediate design states which conversely leads to several steps in the design process to be overlooked (e.g., design intent, editions) [261]. Furthermore, IFC is not supported as a native application file format, leading to information loss when converting from incompatible native software application models to standardised formats [261]. As such, Koch and Firmenich [261] present a new modelling approach named "processing-oriented modelling". This approach completes the traditional (state-oriented) modelling method by recording information about model editions (e.g., editions of objects related to the position or characteristics of materials) which enables the models to present information regarding processes and design intentions with positive results in cases such as combinations and comparison between different versions. Prototype implementations reveal favourable results in capturing the model edition semantics, enabling merging and comparison operations, and certifying model consistency. Limitations to the proposed approach concern the accuracy of the resulting building models that are highly dependent on the correctness of the stored changes. Additionally, sharing design work among different actors still needs further discussion regarding confidentiality and property concerns [261].

Analyse Site Selection Criteria

The diversity of information included in a construction project requires the arrangement of multiple fields of knowledge and actors. In this sense, the combination of information resulting from various software tools may be hindered due to the numerous types of organisation and file formats. Regarding site analysis, the semantic information concerning topography relations with the built environment provided by GIS may support and extend the building information present in the IFC schema. However, the combination of both datasets often results in interoperability issues as there is no standard format to support data exchange between BIM and GIS software [239]. On this topic, Karan and Irizarry [239] explored the interoperability constraints between BIM and GIS regarding preconstruction operations using Semantic Web technologies. BIM and GIS data were converted to RDF, although due to the large amount of information held by both datasets, the authors focused their research on construction site topography and temporary facilities. According to the authors, appropriate combination results are found from the association of SPARQL and XML [239]. Thus, BIM and GIS files should be converted to XML-compatible formats (i.e., IFC and Geography Markup Language (GML), respectively). Additionally, details are given on how to transform a GIS relational database to RDF, as well as derive an RDF from a BIM model. Both datasets were combined into an RDF graph which was then modelled and edited using Protégé 4.3. Finally, SPARQL queries were employed to retrieve the data. Results verify that it is possible to generate a BIM model (Revit) completed with site topography and integrate temporary facilities in a GIS environment (ArcGis) using the proposed framework. Limitations of the proposed approach regard RDF query results' tendency to be rather extensive and produce large files, leading to inefficient retrieving operations since the whole file needs to be read for each query result. Additionally, there is no defined IFC-based standard for SPARQL query results, which leads to consistency issues, such as XML components having more than one ifcXML correspondence.

In another study based on the compatibility issues between BIM and GIS, Karan, Irizarry, and Haymaker [262] targeted retrieving data once converted to RDF/OWL into a BIM model. The authors report using Protégé 4.3 to develop, edit, and map the needed correspondence between IFC and OWL classes, attributes, and properties. Moreover, the semantic similarity was applied between different ontology sources so that similar terms may be translated to OWL or RDF so that results from SPARQL queries could be retrieved. Given that current BIM authoring tools do not support SPARQL query results (e.g., XML, HyperText Markup Language (HTML), CSV, Spreadsheet, or JSON), a framework was devised to map XML to ifcXML format. However, despite validation tests and use-case examples (imported results to Revit) reporting promising outcomes, there are limitations to the application of the proposed approach. For instance, when there is no corresponding concept on the IFC schema, the framework may not retrieve a coherent result.

Author Construction Site Logistics Model

The monitoring of the use and safety of spaces in the construction industry needs further development, particularly in the area of semantic trajectory visualisation and its integration with BIM models [263]. In fact, the monitoring of interactions between operations and operators, and the machines themselves, both outside and inside, may positively influence the adoption of proactive behaviours regarding site congestion, workers collisions, and undue access to restricted areas, among others [263]. In this regard, Arslan, Cruz, and Ginhac [263] propose an approach that targets work and site monitoring by coupling BIM technologies with Bluetooth beacons and data models to enrich trajectories. In particular, an Android application was developed so that building users may report their handheld devices' location data to Bluetooth beacons spread across the building and its surrounding area. Then, data is extracted concerning the users' stay location, speed, as well as stop and move actions, and is laterstored in a database (MongoDB). Furthermore, the authors developed a data model, Semantic Trajectories in Dynamic Environments (STriDE), so that trajectory data such as semantic points, lines and regions could be recorded and pre-processed (this process involved the use of R studio). Trajectories are enriched using semantics from IFC, Open Street Maps (OSM), or RDF files. Finally, a prototype is presented using Revit and Dynamo tools in which semantic enriched trajectories are displayed in different colours throughout the building model. For instance, zones where users have spent more time than necessary are highlighted, indicating an unforeseen situation in need of management. Limitations are also reported related to the operation dynamics and complexity of construction sites, which may harm the Bluetooth beacons and jeopardise measurements. Indoor tracking accuracy is also referred to as challenging in terms of technology, and the system is reported as static, that is, retrieving real-time data still requires further developments due to the offline location data pre-processing.

In another study by Arslan, Cruz and Ginhac targeting the monitorisation of construction sites and semantic trajectories [264], the authors mention the limitations of Behaviour-Based Safety (BBS) and mention the gap of current approaches to identify near-misses in complex settings such as active construction sites. Therefore, an alternative is presented to enrich a BIM model with contextual site information and real-time feedback on building changes, intrusions as well as unsafe worker activities. An ontology-based data model was used (STriDE) to provide adequate semantic information related to spatial-temporal data of workers in an active building environment (cf. [263]). A prototype named VIDEWS (Visualizing Intrusions in Dynamic Environments for Worker Safety) was developed to include the intrusions information displayed in a BIM authoring tool (i.e., Revit) through a plug-in interface developed using Dynamo (visual scripting tool). Additionally, the prototype encompasses Bluetooth Low Energy (BLE) sensor data detected from the workers' handheld devices and the geographical information from STriDe. Overall, the authors' approach intends to support building managers as well as Health and Safety (H&S) managers to avoid hazardous behaviours in construction sites.

Coordinate Design Model(s)

Limited support is given to end-users regarding construction defect data management, mostly due to a lack of organisation when representing the data; difficulties found when trying to access and convey defect data from different sources; as well as inadequate context description [265]. Hence, to support decision-making and enable adequate conditions for actors to access construction defect information, Lee et al. [265] present a linked data framework. The approach encompasses a BIM model for storing construction data, an ontology representing the relationship among the entities, and an interface to query and access linked data from different sources using SPARQL. A defect ontology was developed using Protégé based on collected cases regarding waterproofing. Furthermore, the ontology classes required Onmniclass information to be retrieved from a spreadsheet exported from Revit and converted to RDF. The conversion process, from spreadsheet format to RDF, is established from a custom tool developed in C# using the dotNetRDF open-source library. The authors also report limitations in assigning a classification system using Revit, which led to the necessity of defining Revit families to assign Omniclass codes automatically. Additionally, the use of SPARQL query languages is reported as in need of more friendly interfaces and previous knowledge about the ontology structure is required to establish the queries. It is also mentioned that research should be conducted on how to utilise the extracted query information and import it back into the BIM model (cf. Karan, Irizarry, and Haymaker [262]).

The possibility of modelling linear infrastructures at different scales is not fully supported by BIM authoring tools, so it is necessary to combine this type of solution with GIS software. Thus, the research carried out by Borrmann et al. [266] concerns an approach for the extension of the IFC schema so that it supports multi-scale representations. In more detail, the study focuses on the semantic representation of shield tunnels that should be consistently represented across different LoDs. The approach is based on the use of a procedural description of the geometry to maintain consistency through different LoDs. Therefore, a modification of an object in a LoD will have repercussions on a distinct LoD. The authors describe the semantic mapping of an IFC file to the corresponding CityGML format required for tunnel design analyses to run against geographic criteria despite not all entities being successfully mapped. Through a web service, it is possible to convert the IFC model of a tunnel to CityGML and proceed with the subsequent analysis, such as railway safety. Results from a case study show that the model maintains consistency at different LoDs, facilitates clash detection analysis, and displays environmental surroundings (buildings, streets, public systems) that are affected by the infrastructure.

Analyse Energy Performance

Concerning building performance and thermal analysis, Natephra et al. [267] integrate spatio-temporal sensor data into a BIM model to proceed with indoor thermal comfort and performance analysis. The study encompasses thermographic images and data acquired from various sensors (e.g., dry-bulb temperature, humidity), which were integrated and mapped on the surfaces of a BIM model. The reported method involves the development of an application using Rhinoceros and Grasshopper visual scripting to import the information from an IFC file and enable the visualisation of thermal images over different periods of time as building surface textures. The approach also enables automatic thermal comfort calculations, mean radiant temperature (MRT), and the verification of possible inefficiencies and problems in building envelopes through colour coding. However, this approach does not consider all information exchange using IFC resources. Future improvements realise indoor thermal comfort assessment for air-conditioned buildings, the inclusion of the overall thermal transfer value (OTTV) to improve thermal performance analysis using BIM data, and enhancements concerning image capturing techniques in semi-cloudy environments.

Categories not included in BIM Uses

Although not included in BIM Uses [118], one study reported initiatives towards improved interoperability between BIM and other heterogeneous data deriving from various tools and sources of information. Interoperability is not a "BIM Use" in itself, but it is a relevant research field in terms of SE applications.

Research conducted by Mignard and Nicolle [240] tackles interoperability hurdles to enable better information sharing and communication between BIM and GIS software tools. The authors developed an ontology, SIGA3D, extending the structure of an existing platform for facility management (ACTIVe3D). The extension allows the inclusion of semantics related to environmental and geographic components, which are then converted into graphs. Indeed, through GIS, BIM information can be extended to other domains not yet included in BIM models, such as urban space management and interactions with the buildings' environment [240]. By combining information from IFC and CityGML standards, an interoperable approach to urban facility management is presented, Urban Information Modeling (UIM), to ultimately achieve a certain degree of equality and consistency between BIM and GIS-linked semantics.

2.7.3 Summary

The current inefficiency of integration and combination of multiple sources of information in BIM models, the added laborious manual modelling update effort [226], and persistent interoperability constraints [223], [224], [239] justify the development of multidisciplinary initiatives targeting SE. These initiatives encompass several techniques and approaches (e.g., machine learning algorithms, constrained optimisation methods, ontology-based systems, Semantic Web, and Linked Data technologies, among many others), therefore leveraging contributions from various research fields such as Civil Engineering, Engineering Informatics, Computational Science and Engineering.

This chapter aims to systematise and establish the present status of research in SE and BIM by discussing its key applications, approaches, and limitations. Furthermore, the screened studies are categorised based on their BIM-related project use case.

While considered a relatively emergent research area [232], SE and semantic web services are among the prominent topics and trends in BIM research [14]. Despite the limited bibliography on the subject [232] and the fact that only recently has ontology-based research been considered a prospective approach towards integrating heterogeneous information from various data sources

[260], SE applications provide valuable means to overcome current BIM limitations (e.g., interoperability, enhanced topology relationships, extend standard schemas, among others).

From the screened articles, main developments in SE techniques encompass the use of Semantic Web technologies (e.g., ontology-base systems, integration of SPARQL queries, the use of OWL and RDF files mostly devised using Protégé); inference rules and rule processing engines; artificial intelligence methods (e.g., CNN); ontology mapping and semantic similarity; application of IFC libraries such as IfcOpenShell and server-based approaches (e.g., BIMserver); and custom plugins (e.g., custom code developed with tools such as Dynamo, and Rhinoceros). An overview of the main BIM Uses and computational methods applied to devise BIM-based SE applications is presented in Appendix I.

Concerning current gaps and limitations, the IFC standard is depicted as unsuitable for the uniqueness of certain artefacts related to building heritage domains resulting in a lack of accuracy and consistency [225], [245].

Karan and Irizarry state that there is no defined IFC-based standard for SPARQL query results, which leads to consistency issues, such as XML components having more than one ifcXML correspondence [239]. One aspect to be highlighted in the use of SPARQL query languages is the need for more user-friendly interfaces as well as previous knowledge about the ontology structure to establish the queries [265].

Besides the possibility of combining different building data to coexist in the same graph structure, semantic structures allow querying data by its meaning, which provides an alternative to some of the IFC constraints, such as enabling the possibility of querying multiple models simultaneously [244]. When using ontology-based systems, despite the possibility of representing information from various sources using the same language, developing the ontologies is reported as a time-consuming process [248].

Limitations are also reported when trying to share semantic data between BIM and GIS due to the differences in granularity among the data structure on both platforms leading to only part of the information being able to be retrieved [258].

Considering BIM Uses, most studies corresponded to “Capture Existing Conditions” (nine articles). Indeed, research efforts have focused on the query of HBIM semantics and ways to streamline scan- to-BIM and data integration from site to BIM. “Validate Code Compliance” (five articles) was the second most researched BIM Use, with research focusing on automated compliance checking. “Review Design Model” and “Author 4D Model” verified three articles, respectively, followed by “Author Design”, “Analyse Site Selection Criteria”, “Author Construction Site Logistics Model”, “Coordinate Design Model(s)”, and “Analyse Energy Performance”, with two or fewer occurrences.

BIM has rapidly become implicated in a wider net of technologies and research areas, although a transition to a semantic web paradigm may be limited by its former and standard formats [268]. Future research developments may regard transitions to a more extended and usable BIM paradigm, where the semantics of digital models are concomitant reproductions of their physical duos, i.e., Digital Twins [268]. As such, potential developments may embrace the formalisation of Digital Twinning processes and domain information extensions complying with ISO 19650 [23] to sustain semantic enriched BIM models. Other future research directions may regard general discussion concerning the lack of a standard format for SPARQL query results [239], as well as enhanced support of AECO actors through the transition to Linked Data and ontology-based systems.

As a final observation and attending to the major limitations and challenges highlighted in the three systematic literature reviews, this thesis intends to provide feasible and alternative approaches to combine BIM and immersive interfaces to streamline access to BIM information and overcome reported interoperability issues [82], [91]. Other two driver aspects are the identified need for further research considering users' experience in the real world and their knowledge [121], [177], as well as the recognised lack of a common assessment method to check the suitability and usability of immersive interfaces.

Overall, the present study aims to contribute to the body of knowledge by presenting innovative and generalised means to tap into BIM non-geometrical information and updating construction projects taking into account the diversity of stakeholders in the AECO sector, their tasks and domain-specific knowledge.

3
METHODOLOGY AND RESEARCH APPROACH

3.1 STRUCTURE OF THE CHAPTER

This chapter opens with a description of the main research methodology underpinning the thesis.

The following two sections unpack key notions concerning the concept of usability and usability assessment guidelines for immersive interfaces in the AECO sector, expanding to a methodology for usability assessment in the fourth section.

The fifth section assumes a more propositional tone, introducing an encompassing concept – Natural BIM Interfaces (NBI), centred on the notions of NUIs and Boundary Objects – with the objective of clarifying the scope of the interfaces to be discussed.

The chapter ends with an outline of the proposed solution for the development of immersive interfaces.

3.2 DESIGN SCIENCE RESEARCH

The research approach used in this study is based on the design-science paradigm of Information Systems (IS) [269], which in turn develops from Engineering and the sciences of the artificial [270]. As asserted by Simon, artefacts are not independent of natural laws, yet they are moulded to human intents [270]. Likewise, according to Simon [270], design is concerned with how things should be, with the development of artefacts and the goals they should attain.

The present study also leans on the guidelines discussed by Hevner et al. [269] and the methodology presented by Peffers et al.[271].

Hevner et al. [269] contend that design science strives for utility, whereas behaviour science strives for truth (i.e., justification of theories that describe or predict phenomena), although both are indivisible. As a prescriptive theory branch [272], design science aims to create artefacts (i.e., constructs, methods, models) to answer practical problems [269] and evaluate the feasibility of their application. Design Science Research (DSR) focuses on developing problem-solving artefacts with a clear contribution to the knowledge base [269]. However, Sonnenberg and Brocke [273] argue that prescriptive knowledge can only be validated after application to real practice, which incurs the risk of dedicating a significant amount of time to developing IT artefacts that show utility to an existent class of practical problems. The build-evaluate methodology (cf. [271]) implies that an artefact's truth is only perceived after the evaluation phase, i.e., after the artefact is built or designed [273]. As contended by Sonnenberg and Brocke, DSR evaluations should not be limited to the perspective of descriptive knowledge, which infers in a later phase if a particular artefact is useful and why [273]. Thus, and further according to Sonnenberg and Brocke [273], to elicit real value from DSR prescriptive knowledge, three correlated principles are described:

i) Distinguishing modes of DSR inquiry (i.e., interior and exterior) concerning the evaluation of both design decisions along the incremental design process and the usefulness of the artefact;

ii) Documentation of prescriptive knowledge as design theories which comprises reconsiderations about the common pattern of build-evaluate;

iii) Continuous assessment of the DSR progress achieved through ex-ante and ex-post evaluations by conducting various assessment moments along the DSR process and by following evaluation criteria [273].

Additionally, an enhanced understanding of the problem is elicited by conducting a planned evaluation of the artefact's application from where the design product (i.e., the artefact) and design process may be improved [269], therefore aligning the development of the theory and artefacts by a similar iterative process [274].

DSR does not provide optimal solutions; alternatively, this approach generates an acceptable solution to a practical problem framed by an articulated business need [269]. Indeed, even though artefacts are defined to provide satisfactory solutions to framed problems (i.e., instantiation), they might also possess broad features and characteristics to define a common problem class [272].

3.3 USABILITY ASSESSMENT OF IMMERSIVE INTERFACES

To be fully admitted by the end-users, every system should acutely relate to the requirements and the surrounding environment where it will be employed, thus increasing its acceptability [275]. Systems acceptability can be divided into practical acceptability [276] (related to domains such as cost, reliability and usefulness) and social acceptability when targeting several end-users [277].

Adapted from Gartner's Hype Cycle for Emerging Technologies [278], Figure 24Figure 24 depicts the different acceptability stages of innovative technologies.

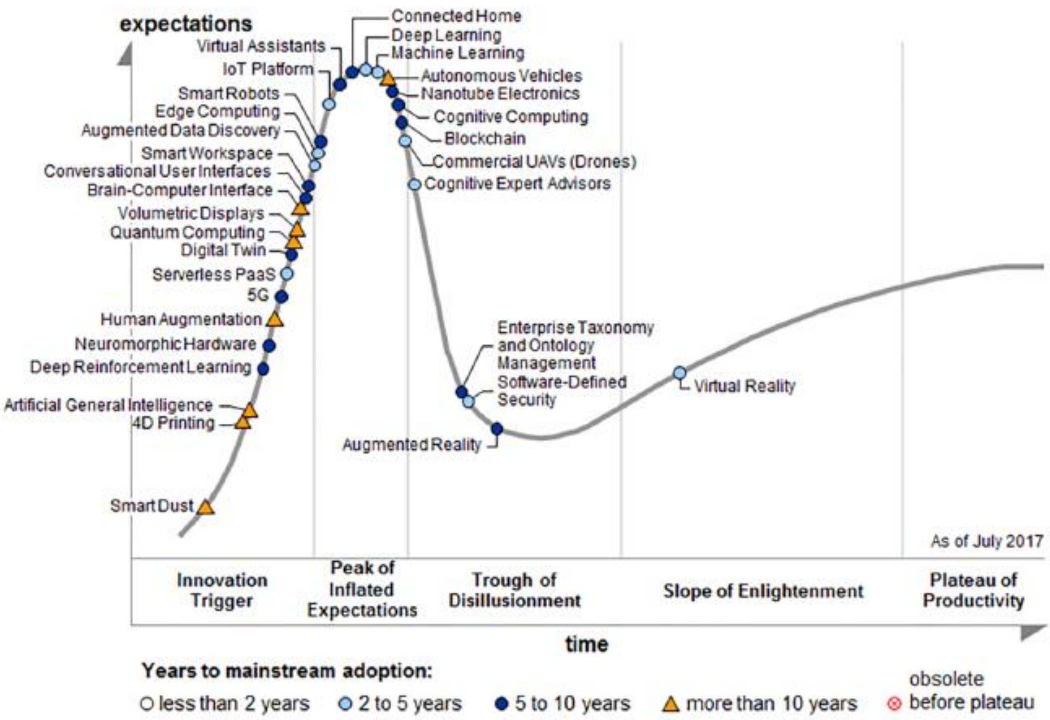

Figure 24 - Hype cycle for key technologies, adapted from [278].

Figure 24 displays that both VR and AR are at the forefront of the cycle, stressing their significant role in emerging technologies and trends.

Comparing the potential benefits and suitability of immersive environments based on VR and AR technology applied to the AECO sector is often hampered by the variety of methods and data treatment techniques employed by current research.

Wang et al. [121] affirm that more comparative tests should be conducted concerning AR tools. Furthermore, the authors determine that despite academic research on validation and assessment, industry adoption is a core criterion for the effectiveness of the technology.

3.4 UNPACKING USABILITY

Although favourable outcomes regarding the use of immersive applications in the AECO sector have described enhancements in performance, efficiency, efficacy and ease of use [41], [44], [88], [90], [95], [245][247], these domains are comprised within a much broader construct – usability.

Systems can be assessed by their easiness of use and compliance with goals to be achieved in a particular environment by a certain type of user. Thus, usability is a common construct applied as an indicator of a system's "capability of being used" [282].

However, defining usability is a challenging task given that the multiple standardisation boards hold different definitions for this construct (see also Bevan [283]), as well as the dependence of usability attributes on the context of usage [284].

A product-oriented approach was established by ISO/IEC 9126-1, defining usability as "The capability of the software to be understood, learned, used and attractive to the user, when used under specified conditions." [285]. ISO 25010:2011 updated the previous standard and considers usability as a category of quality in use while adapting the definition of ISO 9241 [286].

ISO 9241-11:2018 [287] identifies performance and satisfaction measures for usability evaluations as well as the requirement to recognise the goals and the context of use [282]. This standard defines usability as the "extent to which a system, product or service can be used by specified users to achieve specified goals with efficiency, effectiveness, and satisfaction in a specified context of use" [287]. A similar vision is verified in American National Standards Institute (ANSI) 2011 [288], as reported by Sauro and Kindlund [289].

IEE Std.610.12 1990 [290] specifies the same concept as "The ease with which a user can learn to operate, prepare inputs for, and interpret outputs of a system or component.", (cf. ISO/IEC/IEEE 24765-2017).

The model for usability has been the subject of debate by several experts and authors, who consider that more domains could be included as relevant characteristics of the usability construct (e.g., Memorability, Learnability, Security) [276], [284], however proposing different measures to assess them [284]. For instance, the domain of "Learnability" can be defined as the time it takes to learn [277] or become accustomed to some function. However, it should be stressed that some systems are expected to have a steep learning curve as they are tailored to suit specific tasks rather than to be quick to be learned [291]. These systems are designed for the long run, sometimes equipped with tools to tackle detailed tasks. Therefore, they are not meant for sporadic use and imply a longer learning time.

In a broader view, usability is part of a larger network of system acceptability-related concepts. Nevertheless, in terms of practical acceptability, usability may be considered a subfield related to the quality of a system's functionality in terms of usage (see also Nielsen [276]).

To the author's knowledge, assessment methodologies presented in BIM-based VR or AR research occasionally specify usability-related bibliography or standards considerations. Furthermore, the lack of holistic and systematic guidelines should not limit the implementation of such technologies and interfaces to the AECO sector.

This section develops upon the usability models of Dix et al.[291], Benyon [275], Nielson[276], Abran et al.[284], and Preece, Rogers, and Sharp[277], as well as the recommendations of ISO 9241-11[287] and ANSI 2001 [288] to convey a holistic clarification regarding usability evaluations.

3.4.1 Evaluating Usability: formative and summative evaluations

As detailed in the previous section, usability is a challenging concept to define and is mainly related to Human-Computer Interaction (HCI) and design research. Considering that previous studies and standards have shown the prominence of evaluating the usability of systems, the present section exposes guidelines and recommendations for a practical usability assessment methodology for immersive interfaces to be applied in the AECO sector.

Adaptions are considered and may include adding more domains to the known efficiency, effectiveness and satisfaction triad, the need to conduct pilot tests, define usability goals, and apply qualitative methods to better grasp user behaviours. Furthermore, the author elaborates on measuring previously selected usability attributes and providing them in a straightforward display for analysis and possible comparison between studies.

Two main types of evaluation methods are illustrated by Benyon [275]:

(i) Expert-based methods (e.g., formative evaluations); and
(ii) Participant-based methods (e.g., summative evaluations).

Each method and application stage will be further detailed and revised considering the development of immersive interfaces within the scope of the AECO sector.

Formative evaluations

Over the iterative process of designing VR and AR interfaces, the value of formative assessment should be considered, especially during the early development stages. Indeed, initial phases of development are prone to modifications, and changes in the design, which could benefit from input gathered from formative evaluations. A favourable example is the performance of an evaluation steered by usability and/or design experts, where a system is assessed against a list of established design principles. As such, expert-based evaluations comprise a set of HCI experts or usability engineers to test an under-development version of an interface, thus using their experience to compare it against a set of design principles – heuristics evaluation [275]. These known principles, also called heuristics, are a set of "rules of thumb" for the system to be tested against. An example of heuristics based on Benyon [275] and Nielsen [276] is presented in Figure 25.

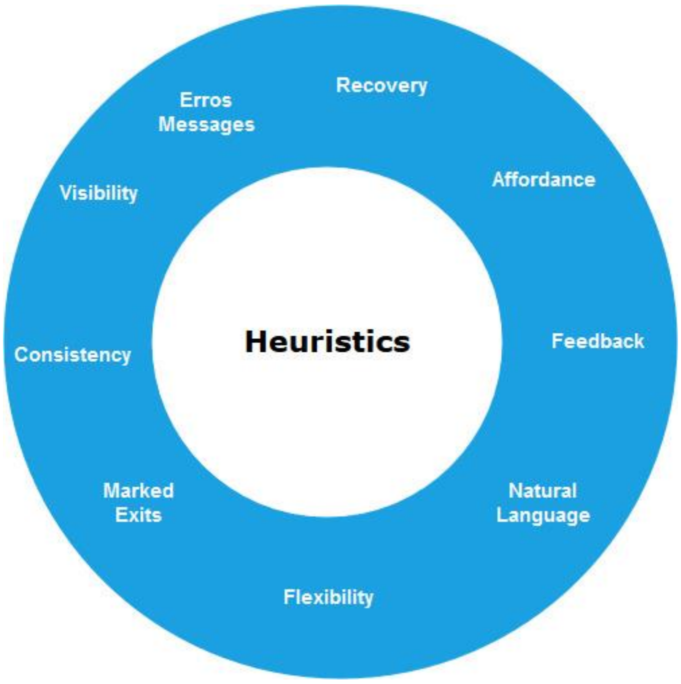

Figure 25 - Design principles used as comparison domains during heuristics evaluation, based on Benyon [275] and Nielsen [276].

Nielsen [276] designates the goal of heuristics evaluations as a means to “find the usability problems in a user interface design so that they can be attended to as part of an iterative design process”. Also, a group of three to five evaluators strikes a balance between a manageable group of experts and the number of problems that may be found during their assessment [276]. The evaluations are independent processes, made separately and without any communication between the experts; only then may results be combined [276]. This kind of assessment is usually carried out during the early development/design phases, where major changes can be pointed at affecting the overall interface [275]–[277].

Examples of these evaluations may be found in Civil Engineering Education, where a formative evaluation of an Immersive Virtual Reality (IVR) system was conducted by Chou, Hsu and Yao [292], comprising suggestions from experts and students.

In another instance, Paes and Irizarry [293] led a case study where a formative evaluation was conducted to assess the usability of an IVR application for design review.

Summative evaluations

A summative evaluation consists of a participant-based method regarding the assessment of usability domains that may comply with international standards (e.g., efficiency, effectiveness, and satisfaction domains as prescribed in ISO 9241-11 [287], among others). This type of evaluation is expected for finished products [277], so the overall quality can be assessed [276] by end-users.

The methodology proposed in this section is based on previous studies, such as Sauro and Kindlund’s [289], where the authors appeal to efficiency, effectiveness and satisfaction as the main dimensions composing the usability construct.

According to Sauro and Kindlund [289], summative evaluations regarding the usability of a target product must attend to the definition and quantification of a set of measures. The authors underline ISO 9241-11 [287] and ANSI 2001 [288] recommendations which determine efficiency, effectiveness, and satisfaction as usability attributes. These domains are established herein as:

- Efficiency: Resources consumed to attain a specified result leading to a certain level of performance [276], [287];
- Effectiveness: The extent attained by users fulfilling and completing with precision a prespecified set of tasks and goals [288];
- Satisfaction: The pleasantness of using the system compared to the user's expectations and needs before the experience [276], [287].

Efficiency and effectiveness are both related to the awareness of task definition. Hence, a list of tasks and sub-tasks should be formulated, and users must explicitly be informed about the tasks to be completed during the usability test. Assuming that every user intends to fulfil the tasks issued, if one misses or does not complete a certain sub-task, it should be accounted as a discount to the overall percentage of task completion (see also Sauro and Kindlund [289]). Effectiveness can, therefore, be measured as the percentage of task completion, whereas efficiency (of use) relates to the time one spends completing a task [276].

Questionnaires are used frequently to assess users' satisfaction. Amidst several examples, the System Usability Scale (SUS) is a well-known tool, comprising the advantages of being a short questionnaire with proven reliability (see also Sauro [294]) as well as generally easy to draw and analyse results from. Each questionnaire answer can be classified using a 5-point Likert scale. The values from the users' answers need to be adapted according to the question number. As such, answers to odd-numbered items are subtracted one value, and each even-numbered item response is subtracted from 5. After adding all the values from each answer, the result should be multiplied by 2.5 [294]. The outcome will lay between 0 and 100 and corresponds to the overall system satisfaction.

3.4.2 Testing Usability: other relevant aspects

VR and AR technologies have been known for several decades, although technological improvements allowing them to be commonly applied are rather recent. Therefore, training sessions may be necessary, especially when most users are unfamiliar with the technology.

Nielsen [276] indicates that to explore some aspects of innovative interfaces without hampering usability tests, novice users who face a transition between interface generations should be subjected to training sessions. In this way, test results will not be skewed due to the users' exertion with unfamiliar interactions and mechanics. Additionally, an experimenter should be selected to run the tests, possibly a person accustomed to the interface and its characteristics [164] (e.g., the designer or developer). It is, though, important to realise that neutrality issues may arise when a designer moderates the evaluation [295].

Although summative evaluations may be suitable for quantitative assessments, the relevance of qualitative aspects should not be overlooked [295], as they may hold an important role in uncovering the behaviour and choices carried out by users.

Li et al. [125] allude to the importance of assessing the sense of presence in VR and AR systems to evaluate the level of engagement and similarity between the simulated environment and the real context. Schaffer et al. [296] report that quality is usually related to the assessment of user perception. In their study on HCI and modality choice, the authors refer to the effect of context and users' subjective preference on user behaviour.

Questionnaires such as NASA-Task Load Index (NASA-TLX) - workload assessment [297], the SUS – perceptions on usability [294], or the Questionnaire for User Interface Satisfaction (QUIS) – user satisfaction [298], can be applied to evaluate users' subjective experience.

3.5 METHODOLOGY FOR USABILITY ASSESSMENT

The following section sets forth guiding principles and recommendations for the usability assessment of immersive interfaces, which will be applied along the practical components of the present study, especially during the case study described in section 3.7.2. The proposed assessment methodology is divided into two parts, i.e., i) under-development interfaces and ii) near-finished interfaces, as presented in Figure 26.

Over the iterative process of developing and designing immersive interfaces, the value of formative assessment should be considered. Indeed, the initial phases of development are prone to more modifications and changes in the design with lesser hurdles when compared to later development stages. A favourable example is the performance of an evaluation, steered by usability and/or design experts, where the system is assessed against a list of established design principles, also called heuristics. Preliminary pilot tests should be performed as a cautionary and best practice to foil possible inconsistencies and work on unnoticed misplaced assumptions about tasks design, plan or procedures [276].

This stage (i.e., formative evaluation) should be iterative until most usability issues are recognised (following a set of recommended design principles – heuristics) and further corrected.

When a near-finished product is achieved, participant-based evaluations, such as summative evaluations, allow target users (i.e., participants) to assess the proposed system. During this stage, measurement tests become adequate to gauge the outlined usability attributes. However, reflecting on the weight of the chosen usability attributes and planning the usability goals is paramount and can be considered a rather difficult process compared to new versions of existing solutions [276], as these may benefit from previous usability studies or guidelines.

Figure 26 depicts an overview of the proposed stages for a usability assessment methodology.

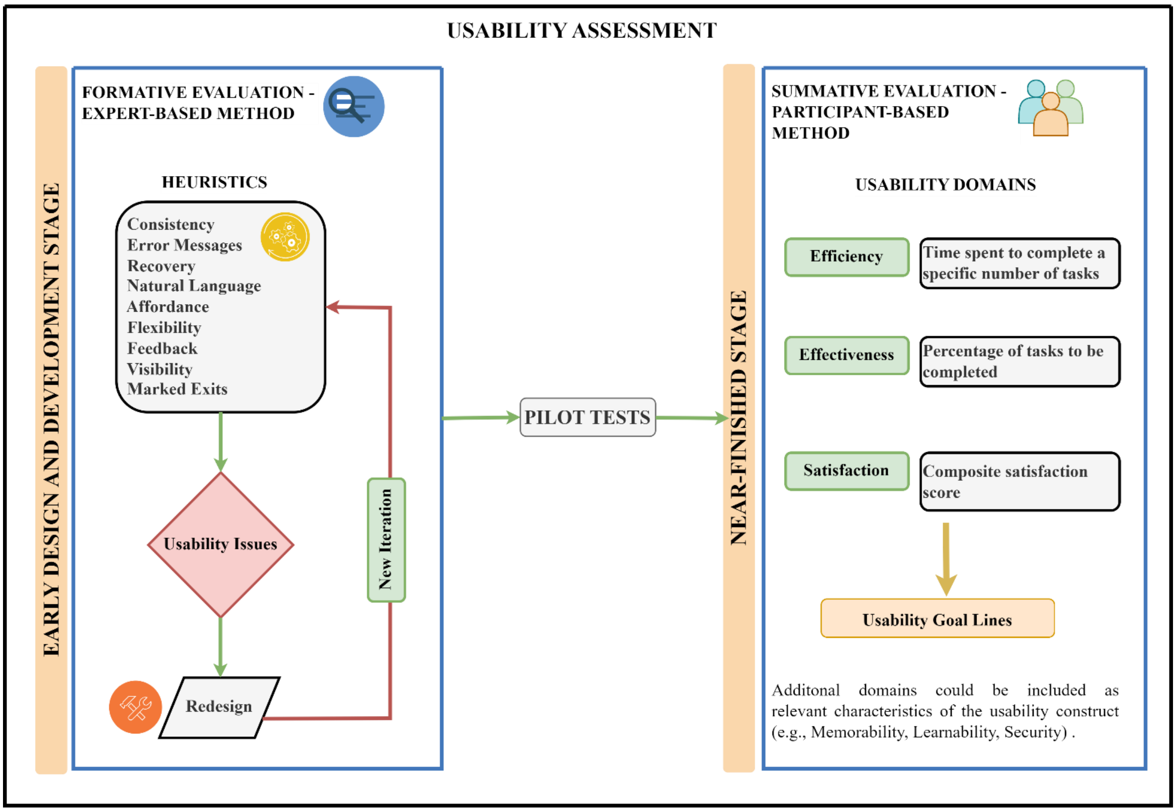

Figure 26 - Proposed guiding principles for a usability assessment methodology.

A scale transformation is necessary to ease the comparison between usability attributes. For instance, efficiency is measured as time, whereas other variables, such as effectiveness, or satisfaction, are defined on a scale between 0 and 100 (i.e., percentage values).

Taking into consideration the following example of a straightforward test scenario where no breaks are required - despite the absence of a general rule to establish the duration of tasks, Preece, Rogers and Sharp [277] state that one should propose breaks if a task is designed to take more than 20 minutes - defining acceptable boundaries for theoretical minimum, maximum, and target times could be useful to assess the completion of pre-set tasks. Therefore, it is possible to establish the target time span for different Efficiency intervals and transform them into percentage values.

Figure 27 shows a possible transformation approach for the Efficiency attribute based on the setting of a usability goal line (see also Nielsen [276] and Rideout [299]) so that it can be presented on the same scale as the other two usability domains (i.e., effectiveness and satisfaction).

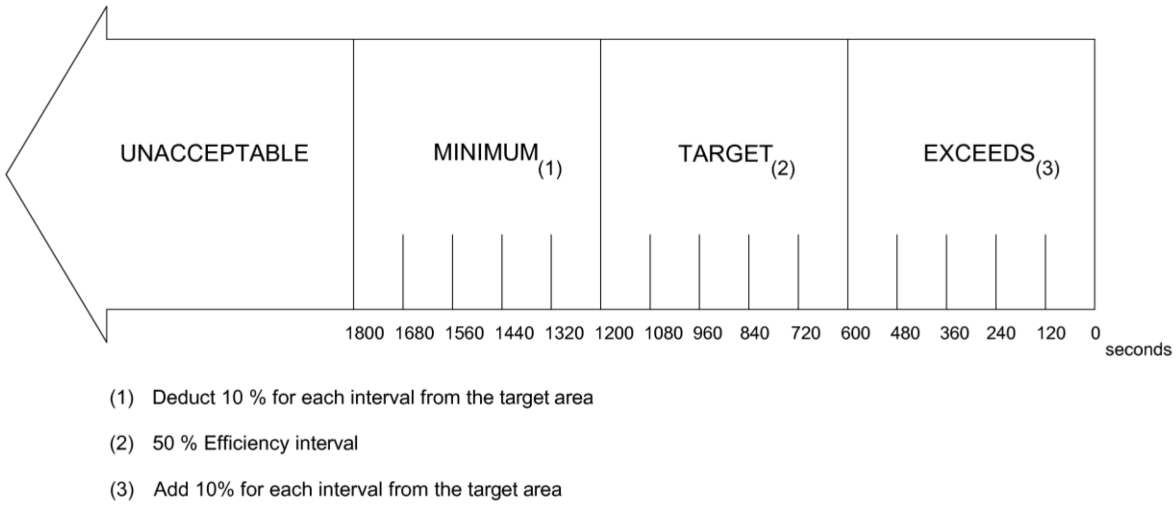

Figure 27 - Proposal for an efficiency scale transformation, based on [276] and [299].

According to the intervals and areas presented in Figure 27, a percentage can be assigned to the time it would take a user to complete a particular task. In each of the four areas, limits can be pre-defined based on the previous experience of usability experts. As part of a summative evaluation, these intervals establish theoretical minimum, maximum, and target times for completing a task.

Users who complete a task within the "Target" score 50% Efficiency. The final rating for other users with time scores below the lower limit of the "Target" is 50% plus 10% for each interval until the task completion time (i.e., the number of seconds spent to complete the task).

Conversely, users whose time to finish a given task is above the upper limit of the "Target" area will see their final classification increased by 10% up to the interval that corresponds to the number of seconds remaining.

A user’s time will be considered "Unacceptable" if the maximum time is exceeded, and a 0% Efficiency score will be assigned.

The three usability attributes may be analysed and presented in box plots to present comparative results, such as those depicted in Figure 28. Each attribute's median represents the 50% percentile (darker lines), while the 25th and 75th percentile are limited by the lower and upper parts of the boxes, respectively. Whereas the mean is more prone to be influenced by extreme values, the median offers a more appropriate measure in the presence of such values. The upper and lower

T-bars present the minimum and maximum values, not accounting for the outliers. Outliers denote extreme values, out of the range of the T-bars, marking the inner fence, that is, 1.5 times the extension of the box [300].

This approach may enable a more practical comparison between usability studies targeting similar interfaces and applications.

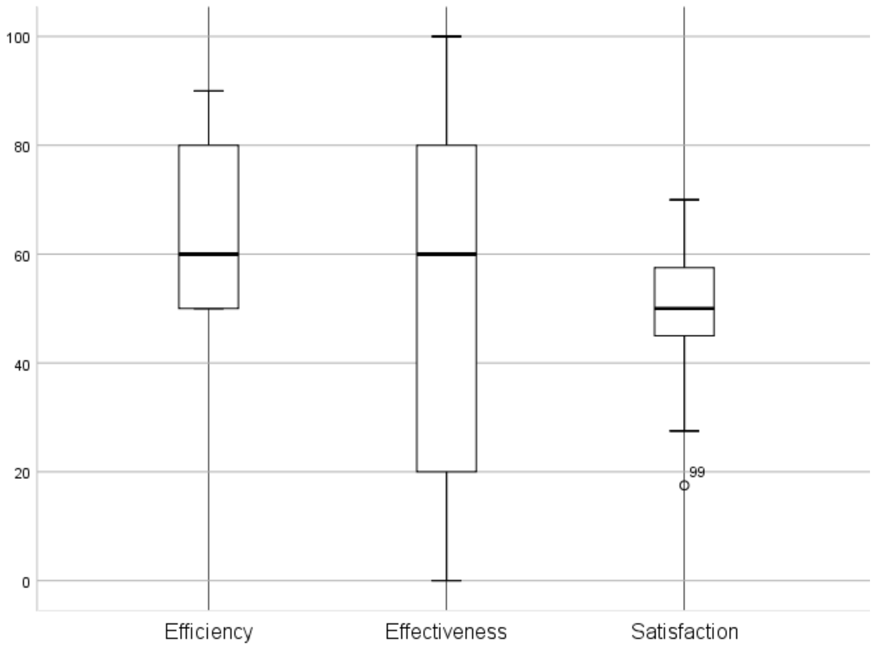

Figure 28 - Possible Box Plots pertaining to the three usability attributes ranged in a score scale of 0 to 100.

3.6 IMPROVING ACCESSIBILITY TO BIM: NATURAL BIM INTERFACES

Ku and Mahabaleshwarkar [301] stress the benefits of virtual environments to access BIM towards Construction Education and present the notion of Building Interactive Modelling (BiM). Similarly, although within a broader scope, this work implements the concept of an NBI initially presented by Dinis et al. [35]. NBIs integrate BIM within a framework to enable a sense of instant expertise and direct access to project information. In a broader sense, NBIs comprise a set of processes and devices that, through the reuse of actions common to other contexts, enable accessibility to BIM, maximising the ratio between performance and effort.

BIM authoring tools encompass a set of systems designed to handle specific tasks, usually holding many features and not meant for short-term and momentary usage. Hence, this type of tool, intended for the long run, frequently substantiates a steep learning curve [134]. Furthermore, a higher cognitive load is patent in some BIM tools, making them unsuitable to be used by the variety of stakeholders and actors involved in construction project teams. In this regard, NBIs aim to increase the permeability of construction information through BIM, consequently adapting to the various layers and demands of AECO teams. Additionally, the exchange of information between teams, stakeholders and amidst functional levels is established through "Boundary Objects" [302], in this case, NBIs, adapted to the tasks, environment and demands of the different end-users.

Boundary Objects are endowed with distinct meanings in several fields yet reveal entities with a common structure to different users [302]. They provide enough flexibility to adapt to the needs and backgrounds of end-users, becoming significant tools to access information and enable collaborative work [303]. Based on Dinis et al. [35], Figure 29 displays an overview of possible NBI-based communication and interactions amidst construction project teams around the notion of Boundary Objects (see also Taylor [304]).

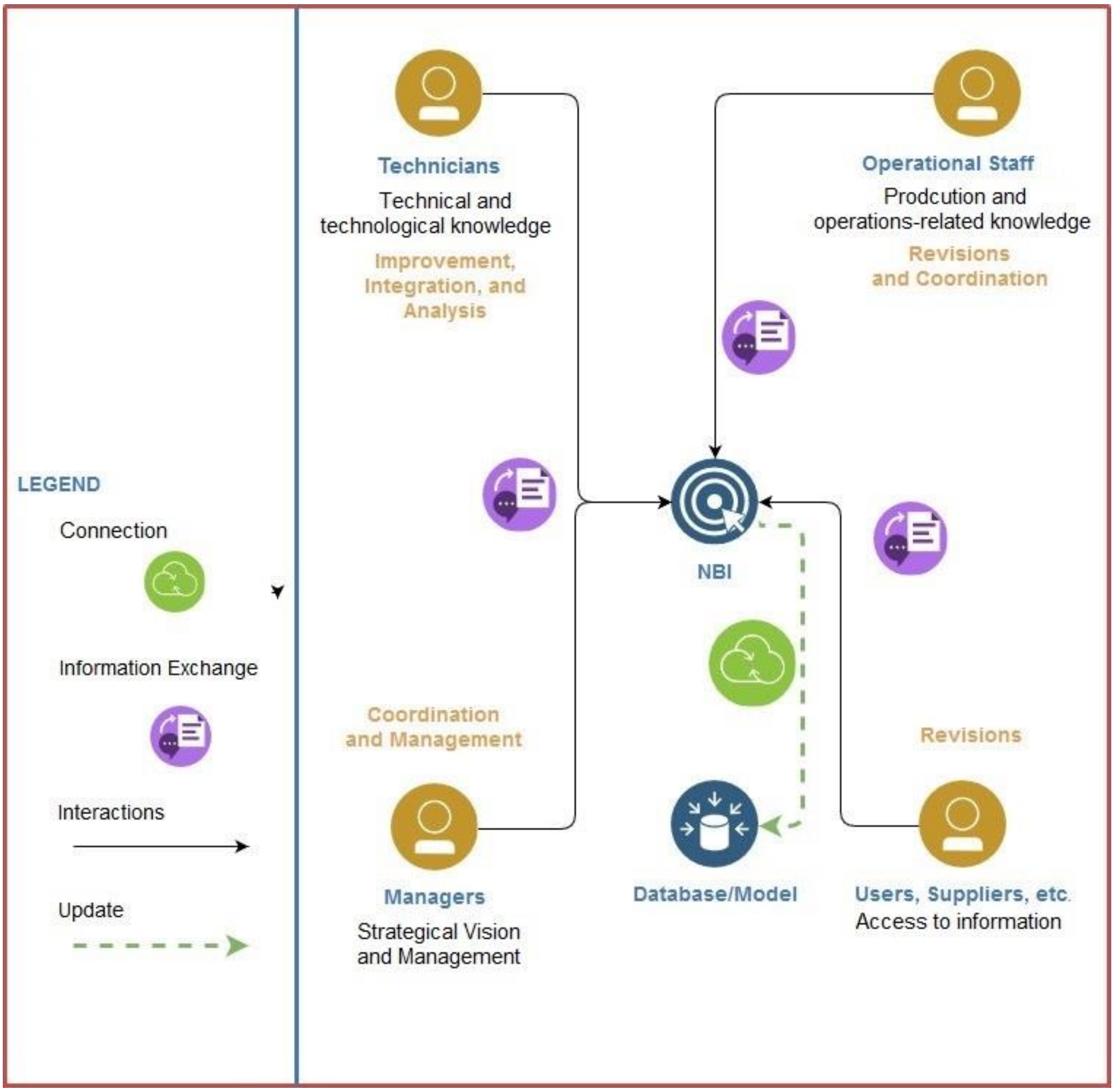

Figure 29 - Users' interactions with a Boundary Object (NBI).

According to the purpose of Article 22(4) of the Directive 2014/EU [24] declaring that: "For public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar. (…)", public procurement is encouraged to appeal on the use of solutions such as BIM. The recent approval of an international standard for BIM (ISO 19650-1:2018 [23]) on project life cycle information management supports an expected paradigm shift and the resulting need for adaptation. In fact, BIM is already a requirement for public procurement in countries such as Norway, Denmark, Finland, South Korea, Singapore, the U.S.A. and the U.K. [305]. Additionally, during the last few years, several governments and industry initiatives have been witnessed [22]: U.K.: UK BIM Task Group; Brasil - Comité Estratégico de Implementação do Building Information Modelling – CE-BIM; France - Plan Transition Numérique dans le Bâtiment (PTNB);

Spain – EsBIM; Portugal - Comissão Técnica de Normalização BIM, CT 197; Germany - planen-bauen 4.0 (2020).

AECO companies are now faced with the possibility of leaping into a paradigm shift with a reasonable amount of uncertainty on how to do it without losing efficiency and avoiding losses regarding ROI with formation and equipment. Hence, the proposal of NBI conforms with the possibility of introducing BIM to key players within the sector while simultaneously delivering a more inclusive workflow.

Figure 29 displays the roles and actions of different actors centred on interactions with NBIs (i.e., the Boundary Object). As such, NBIs operations are twofold:

- Interactions: improving collaboration and streamlining digital and information-based communication;
- Processing: drive and democratise access to real-time BIM data exchange.

NUIs are thus within the range of technologies that may support the development of NBIs for advancing collaborative and inclusive BIM-based systems. Indeed, studies have found that BIM should be adapted and supported by other technologies to increase its acceptability by different users [3], [15], [25].

Although thoroughly detailed in chapter 3, one aspect that should be highlighted concerns possible approaches to validate NBIs. Notwithstanding previous initiatives towards methodologies for validating new interfaces and their integration with BIM [31]–[33], their scope is confined to a certain type of technology or domain-specific activity. Thus, a gap is identified concerning the need for a holistic evaluation tool to ascertain the suitability of NBIs. Also, guidelines for a general methodology to validate NBIs should consider user tasks, their requirements and adapt to the various phases of construction projects. The case study described in section 3.7.2 is supported by a thorough usability assessment addressing the abovementioned concerns.

3.7 PROPOSED SOLUTION OVERVIEW

The technological paradigm shift and the gradual implementation of innovative IT processes in the AECO sector hold the prospect of enhanced collaboration between the industry actors [306], thus bringing benefits for the exchange of building information. However, current research has highlighted an ongoing lack of awareness regarding the benefits and responsibilities of each stakeholder concerning BIM [3]. The need for a significant investment in training, education, and additional software and hardware requirements [26], [27], [307], followed by the reported lack of confidence, motivation, know-how and difference in skills toward BIM [8], [18], present current challenges for a comprehensive uptake of BIM-based tools. Furthermore, research has acknowledged the need for increasing supportive technologies that enable the use of BIM, considering the available human resources, their requirements, and the tasks that they perform [25].

In recent years, the development of immersive interfaces for the AECO sector has provided new opportunities for collaboration [79]–[81], [84], [90], [91], [111], [112] alongside further benefits such as reducing the technological skill gap by coupling NUIs and HMDs [112], [160], [308].

Despite the favourable results reported by previous initiatives where BIM-based immersive VR was applied to the AECO sector [115], [309], a holistic, systematic assessment methodology or guidelines is lacking [115] to provide comparable results between immersive interfaces aiming at similar tasks. Moreover, considering the reported challenges to a full-fledged acceptance of the BIM methodology and the generalised use of BIM-based tools, the author reflects on the relevance of developing innovative interfaces that are more attuned to the tasks, requirements, and working environments. These interfaces should be designed to prevent the exclusion of sectors of construction project teams that might be less familiar with BIM methodology and current tools. In this regard, the proposed solution encompasses two phases:

i) System design and development; and

ii) Usability evaluation.

The system design and development phase started by developing a proof of concept to update BIM projects, combining VR technology and laser-scanning. The proposed system allows users to navigate within the environment and communicate with the project team through notes made in the VR scene using voice inputs. The information (speech notes) is semi-automatically transferred to the corresponding BIM model by instantiating objects – family instances – containing the spoken notes in the same location as in the VR environment.

This prototype's development and runnability test (detailed in section 4.2) established the basis for further advancements since most of the scripts related to voice interactions, movement, and selection mechanisms were reused while designing and improving the second NBI.

The second interface consists of an openBIM VR-based system for the semantic enrichment of BIM models, validated by construction projects facility management operational staff according to a detailed usability assessment methodology. In addition to the design and development stage, the proposed system was part of a usability evaluation conducted during the early stages of development (i.e., formative evaluation to recognise most usability issues at an early stage), followed by a later assessment during the near-finished phase. Figure 30 summarises the overall solution proposal.

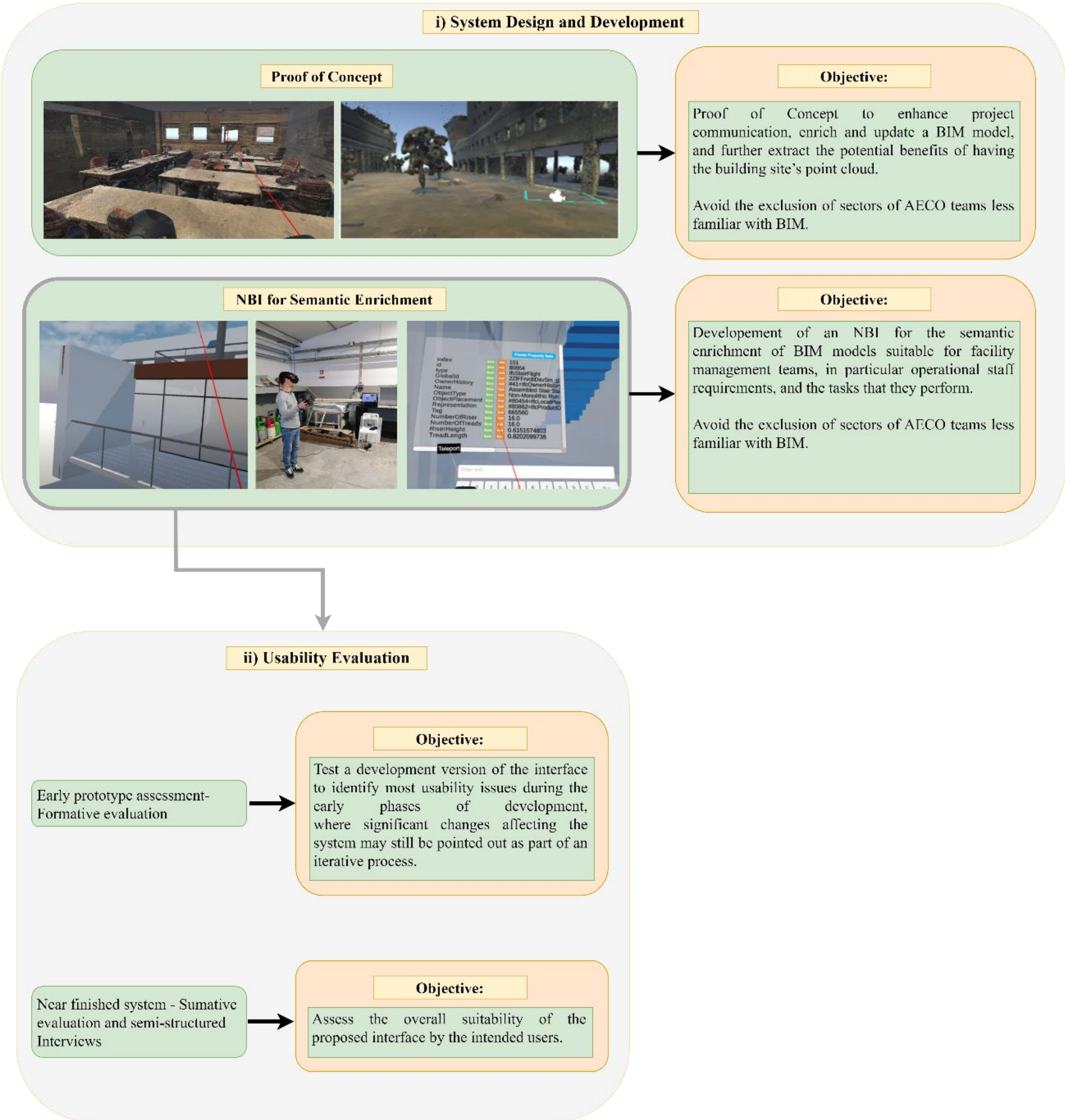

Figure 30 - Overall solution proposal.

An analysis of the context, related work, and technology underlying each interface is provided in the following sections, along with its relationship with BIM.

3.7.1 An NBI for enhanced communication between project-related entities — coupling VR and laser scanning

In recent years, laser scanning has been increasing its importance in the AECO sector, being applied in several areas such as: project monitoring [310]–[312], automated BIM [313]–[315], and retrofitting [316]–[318]. The latter, in particular, has received the support of several international strategies [319], [320] aimed at accomplishing existing industry goals, particularly related to energy efficiency and CO2 emissions [321]–[323].

In spite of the urgency of such goals, multiple challenges continue to exist within the retrofitting process, often related to inefficient communication between the parties involved as a result of the lack of knowledge about the as-is state of the building and the unavoidable involvement of multiple AECO professionals and stakeholders during the retrofitting process and the buildings' life-cycle [323]–[325].

A brief introduction to laser-scanning for building geometry acquisition

Latest technological advances allowed for the development of detailed three-dimensional (3D) representations of the as-is building [325], [326] acquired through survey technologies such as laser scanning, photogrammetry, videogrammetry, time-of-flight, optical triangulation, among others [324], [327]–[330]. However, as seen in [80], [331], [332], laser scanning has emerged as one of the most relevant topics in the field of BIM since 2017, appearing in the top-ranked clusters of knowledge and keywords, and is the topic of one of the most cited articles [333]. Indeed, laser scanning's capacity to perform automatic and quick measurements of distances and angles, combined with its highly accurate capture of complex geometries and minute details, distinguishes this technology in comparison with the remaining alternatives [326], [330], [334]. Furthermore, the development of expert point cloud software, such as Leica cloud CYCLONE, MeshLab and Autodesk ReCap, allows for the quick processing of the acquired data, permitting the elimination of unwanted noise, the alignment and unification of the point clouds and the conversion of this data into geometric forms [324]. In fact, through this conversion, laser scanning may provide the means for the automatic generation of BIM models, easing the effort to create as-is models while also improving their accuracy and detail. Several research initiatives have focused on the so-called "scan-to-BIM" process with positive results [333], [335]–[338], dividing the process into three main steps: data collection; data processing; and BIM modelling.

Despite this, laser scanning still has limitations, requiring expensive equipment and knowledgeable operators. Additionally, its field of view may also be a problem, forcing the user to acquire multiple point clouds from different positions to eliminate occlusions, as seen in [321], [326], [335], [339].

Another aspect worth mentioning is that BIM still faces limitations concerning the adaptation to the knowledge levels, skills and tasks of different project teams [15], [25]. Therefore, the development of VR scenarios may provide more intuitive, interactive and understandable environments to meet the profiles of a broader range of users.

Developing suitable VR environments for the AECO sector represents an even more challenging task attending to the possibility of having to portray a continuously changing real built environment, whose information is often difficult to acquire. Thus, deriving 3D virtual scenarios from point cloud data can significantly reduce the modelling effort necessary to achieve a visually accurate VR environment. As such, VR and laser scanning have previously been applied with a wide range of uses: Brenner and Haala [340] present a method for fast producing VR models of cities using airborne laser scanning; Fernández-Palacios et al. [341] demonstrates the benefits of using laser scanning and VR in relation with cultural heritage, by producing detailed and photo-realistic virtual environments useful for visualisation, documentation, promotion, museum exhibitions, virtual tourism, among others; Bruno et al. [342] suggest guidelines for the creation of a virtual exhibition system for realistic high-quality archaeological findings; Barreiro and Fritsch [343] detail the challenges of surveying historical cities, presenting a methodology based on laser scanning and photogrammetric techniques for the generation of visually aesthetic and detailed 3D virtual environments; Kersten [344] also displays the potential of coupling these technologies through the creation of a VR model for a portion of an ancient dam.

The proposed NBI (proof of concept) was developed to demonstrate the benefits of the joint application of VR and laser scanning within a BIM environment, aiming to enhance project communication, enrich and update a BIM model, and further extract the potential benefits of having the building site's point cloud. These objectives are accomplished through the proposition of a workflow, followed by its validation in a proof of concept (see section 4.2).

Research Approach

The framework for implementing the research approach is summarised in Figure 31 and comprises six steps consistent with Peffers et al. [271]. Additionally, similar problem-based approaches to AECO-identified challenges can be found in the works of Ding et al. [345], Pradeep et al. [346], and Schimanski et al. [347].

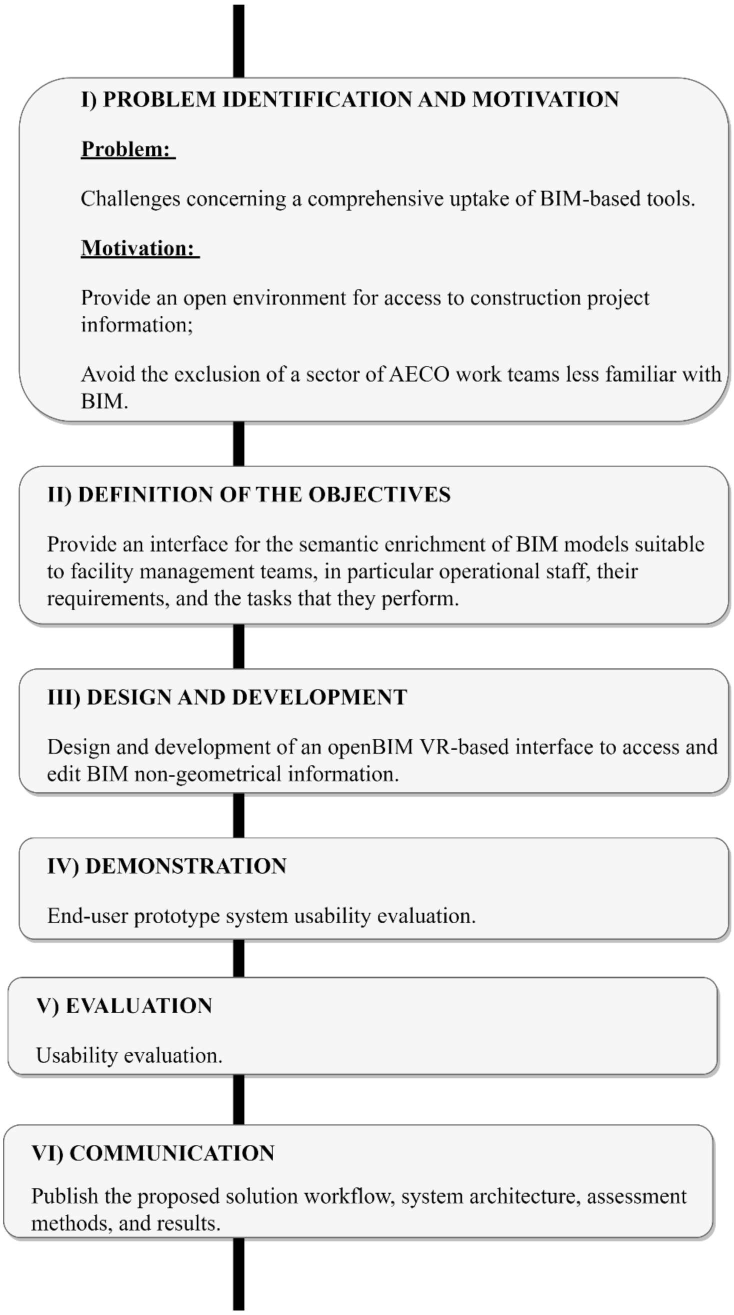

Figure 31 - Framework for implementing the research approach consistent with Peffers et al. [271].

3.7.2 An NBI for Semantic Enrichment

Considering that most BIM authoring tools require a level of expertise and understanding that is beyond the reach of most actors involved in construction project teams, the proposed solution contributions are two-fold: a proposal for a VR-openBIM framework is presented, particularly for the semantic enrichment of BIM models, and a methodology for evaluating the usability of this type of system in the AECO sector. Thus, two research questions arise:

i) How can immersive VR interfaces coupled with NUIs improve access to BIM models' semantic information?

ii) How suitable is the proposed system for accessing and editing BIM information among professionals in the AECO sector?

To answer the proposed research questions, the author proposes a framework encompassing an open data transfer and storage system based on VR for the semantic enrichment of BIM models, evaluated according to a usability assessment methodology (cf. section 3.3 to section 3.5), and later tested and validated by construction projects facility management operational staff to ascertain the suitability of the interface. The system is centred on the IFC schema for data transfer and interoperability and provides a module for validating user changes to underlying IFC file – through inputs made in the VR environment — against custom Information Delivery Specifications (IDS) [219]. Also, the proposed VR environment features voice and gesture commands to filter building element sets and interact with IFC information. Furthermore, the work herein is based on the DSR methodology for designing the artefacts corresponding to the practical problem of providing improved access to BIM information (cf. section 3.2).

A case study is presented following a thorough usability assessment methodology comprising formative and summative evaluations. In particular, qualitative data collection from formative evaluations and 62 semi-structured interviews with construction projects facility management operational staff. Quantitative data analysis of identified usability domains (e.g., effectiveness, efficiency, and satisfaction) followed by results corresponding to pre-established usability goals are also analysed.

Related work

The application of IT equipment providing immersive visualisation and interaction with BIM models has become increasingly common in recent years [115]. In particular, technological developments (e.g., graphics and tracking technologies) [192], [348] and the increased affordability of HMDs [83] have enabled their use in other areas of knowledge beyond HMDs' most common usage (i.e., the gaming industry) [349]. In the AECO sector, the use of head-based VR platforms [350] to devise BIM-based environments has enabled a substantial amount of research with positive results in applications for collaboration within project teams [80], [90], [351], facility management [91], [351], design review and supporting decision-making process [352], [353] construction safety [96], engineering education and training [46], [280], [354], among many others.

As collaboration and shared understanding are essential when working with teams comprising different backgrounds and knowledge levels, the application of immersive interfaces (e.g., HMDs-based interfaces) may enable improved simulation of users' 3D perception compared with non-immersive interfaces, thus enhancing spatial understanding [353]. Additionally, Paes et al. describe that HMD-based virtual environments benefit design-review tasks as they provide greater levels of presence [353].

In his research, Wolfartsberger [348] describes the benefits of conducting design reviews through VR interfaces. Also, the author argues that in addition to the possible loss of the sense of scale when performing a design review through a screen (i.e., non-immersive interface), there is also the risk of excluding particular professional groups who are not entirely familiar with the type of software being used [348]. Indeed, and in the specific case of BIM authoring tools, most software requires a level of expertise and knowledge that is not within reach of all members involved in construction project teams. Thus, immersive interfaces may provide an alternative approach to interaction and a combined understanding of BIM information, data integration and transfer amongst project teams.

As stated by Rahimian et al. [160], enhanced visualisation enabled by technologies such as VR promotes more democratic access to BIM models and improved understanding by non-technical professionals, therefore overcoming the termed “black-box effect”.

Besides displaying BIM geometry, immersive environments are also used to access information concerning the project and its building elements, i.e., non-geometric information. Zhang et al. [350] state that VR systems should display and retrieve specific project information capitalising on human interaction and attention, thus requiring further research in this field. In this regard, commercial solutions have been developed, presenting alternative workflows to overcome interoperability hurdles between BIM authoring tools and other software, such as game engines, enabling the rapid development of immersive experiences. Unity Reflect Develop [187] and Datasmith export plugins [355] are two proprietary solutions to upload and link BIM models to VR scenes within a game engine.

In contrast, previous initiatives have tackled open-source workflows to integrate non-geometrical information into immersive environments [192], extending the role of VR aside from the sheer visualisation of BIM models [192].

Nandavar et al. [192] devised an IFC-based bidirectional data transfer solution targeting collaboration and layout safety planning. In detail, the authors highlight that exporting FBX (.fbx) or OBJ (.obj) files from BIM tools to Unity game entails several limitations, such as being a repetitive process and including loss of non-geometrical information [192]. The solution proposed by Nandavar et al. [192] comprises two layers. One layer is responsible for parsing the geometrical and meta-data of the BIM model contained in a customised XML file and importing it to the game engine (i.e., Unity); a second layer concerning the conversion of changes made in VR to an XML file, afterwards parsed using the xBIM C-sharp (C#) toolkit and converted into a new IFC file [192]. Also, the proposed VR prototype features a walkthrough, measurement tool, visualisation of building elements’ meta-data (i.e., non-geometrical data of the BIM model), moving and deleting building elements, making points of interest, and taking snapshots [192].

Hilfert and König [83] describe a workflow to import BIM models’ geometry and material data as an IFC file into a game engine (i.e., Unreal Engine). The solution comprises a custom plugin to connect users to BIMServer, and then process the geometry as a binary representation, which is later parsed and displayed in the game engine. A custom database was also devised to map different materials to the correct building objects.

Concerning a bidirectional solution to enhance end-user and non-technical collaboration in the design process, Edwards, Li, and Wang [84] suggest using the IFC schema to improve openness and allow for more semantic data to be acquired.

Rahimian et al. [160] present an IFC-based system to enhance stakeholder participation and collaboration in the design process, establishing real-time integration of BIM models into immersive environments. The proposed solution focuses on an openBIM cloud-centric approach and describes the development of a C# library to overcome compatibility issues between IFC and Unity’s geometry interpretation and enable developers to query and manipulate IFC entities. Also, a virtual showroom prototype to support client participation in the design process through an immersive VR environment is presented, featuring a model walkthrough, wall material and colour picker, an option to toggle light switches, and the display and manipulation of IFC data, albeit little information is provided concerning user interaction with BIM information. The authors report that usability tests were conducted to allow further prototype iterations by gathering feedback from 20 participants. However, no information is provided regarding questions or the validity of the applied questionnaire.

Khalili [46] states that enhancing interoperability between BIM and VR environments may provide new semantic enrichment possibilities and benefit the different phases of the project life cycle. However, data exchange between BIM and VR is still a demanding process faced with various interoperability hurdles despite reported research efforts [356]. Among the most commonly reported issues stands the data structure not being compatible from one software solution to the other [356], [357], besides the whole process being time-consuming, especially in the case of large BIM models [356].

Another article by Khalili [356] presents a prototype solution to transfer geometric and semantic information from a BIM authoring tool to a game engine at runtime. The solution consists of a prototype that exchanges Autodesk Revit and Navisworks data to an XML file (forward process) through add-ins and applies changes made in VR into a new IFC file (backward process). Task schedules and clash detection information are provided within the VR environment dedicated to construction management information. Despite laboratory performance tests verifying the efficiency and possible benefits of the proposed solution, no user assessment tests were performed to verify the suitability of the system against AECO users' requirements and needs.

While previous research describes favourable outcomes regarding performance, effectiveness, and ease of use of immersive interfaces for the AECO sector [96], [106], [280], these domains are contained within a much broader construct – usability. However, usability testing references to standards or best practices are largely absent from the literature concerning VR research applied to the AECO sector.

The proposed solution aims to provide a framework for developing a VR full-fledged openBIM system for accessing BIM information. In particular, it consists of a prototype presenting a practical means for the semantic enrichment of BIM models, especially for facility management tasks, harnessing non-technical and operational staff empirical knowledge. Furthermore, a complete usability evaluation was conducted to validate the suitability of the proposed solution to meet the requirements of the AECO maintenance and facility management operational staff.

Research Approach

The research approach for the development of the proposed interface is depicted in Figure 32 and is based on the DSR methodology for designing artefacts corresponding to practical problems, as previously detailed in section 3.2.

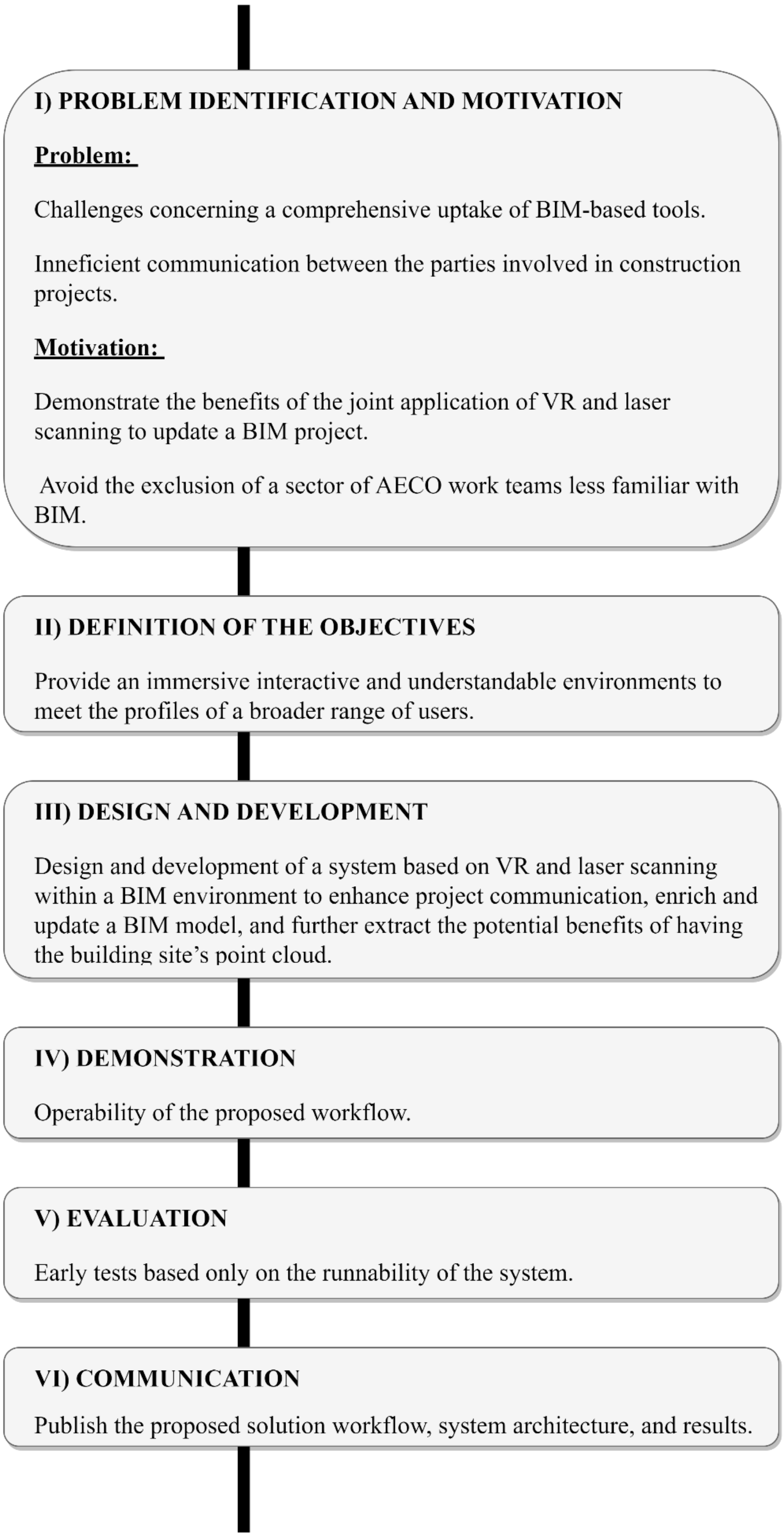

Figure 32 - Outline of the research approach consistent with Peffers et al. [271].

The following chapter describes the development steps of both NBIs and elaborates on the application to a case study.

4
DESIGN, DEVELOPMENT AND VALIDATION OF NBIS

4.1 STRUCTURE OF THE CHAPTER

This chapter describes the development process of two NBIs in detail.

The initial development steps and laboratory assessment of a proof of concept for enhanced communication between project-related entities by coupling VR and laser scanning are described in the first section. Then, the particulars concerning the development of an openBIM immersive interface for semantic enrichment and its usability assessment are presented in the second and third sections of the chapter, respectively.

4.2 NBI COMBINING VR AND LASER SCANNING — WORKFLOW OVERVIEW

This section presents a complete overview of the proposed workflow for the first NBI. In summary, the workflow uses a laser-scanner point cloud to set a building's geometry within a virtual environment and enable users to relay information (i.e., spoken strings of text) to the design team through interaction within VR. This information input is then updated to enrich the project's BIM model to be addressed by the design team.

The proposed system consists of five software tools that can be roughly divided into three groups:

- Point cloud software;
- VR software; and
- BIM modelling software.

Factors that affected the selection of the software for each group are multifaceted. However, a heavy influencer in the final decision was the software-documented interoperability.

In the first group, Leica Cyclone 9.1 and MeshLab were applied for their well-documented interoperability with one another [358], [359], as well as with the used laser scanner Leica's ScanStation P20 [360], [361]. In the second group, the Unity game engine, a cross-platform game engine which has been applied in recent years for the development of immersive VR environments in AECO applications [81], [109], was selected to create the virtual environment. Furthermore, the game engine's recognised interoperability with MeshLab was also a deciding factor [362], [363].

Concerning the BIM modelling software, Autodesk Revit and Dynamo (an open-source plugin in Revit for visual programming) were used for their current dominance in the scientific and professional community [325], intuitive and powerful modelling capabilities [364], as well as the well-documented interoperability with Unity [91], [365].

The following sections describe each required step to accomplish the workflow purpose. These sections follow the workflow in Figure 33, divided into three groups: Point cloud acquisition and treatment; VR environment; and BIM project update.

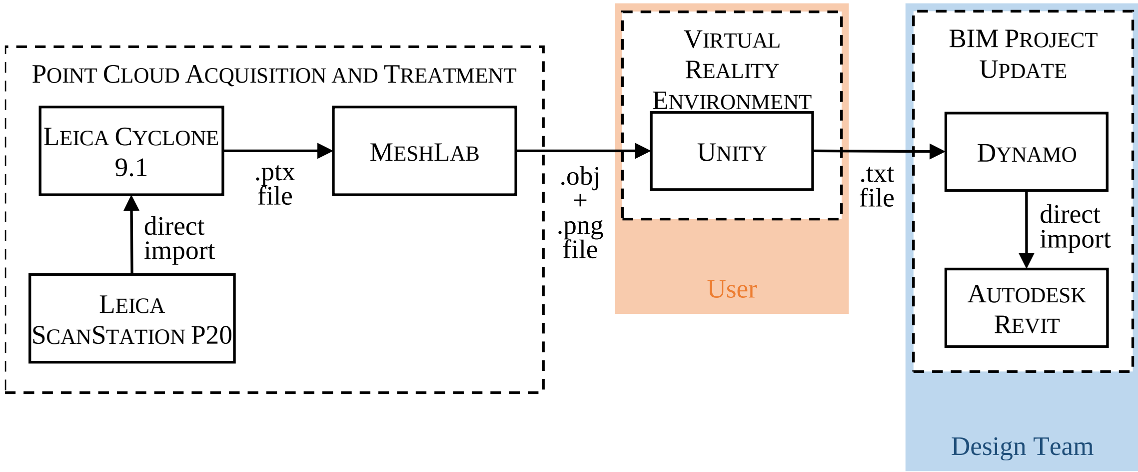

Figure 33 - Proposed workflow, adapted from [351].

4.2.1 Point cloud acquisition and treatment

The first step in the proposed workflow is the laser scanner surveying of a group of buildings of the Faculty of Engineering of the University of Porto, followed by the treatment of the acquired point cloud using a point cloud software, and finally, its exportation to a mesh creation software. The initial parts of this step have been detailed in [318], where the authors propose and apply a framework for the acquisition and treatment of a building's as-is geometric data using laser scanning. This process includes the planning and setup of the required scan locations, the exportation of the acquired point clouds from the laser scanner to a point cloud software and, lastly, the registration (i.e., the process of merging multiple scans in a single-shared coordinate system) and cleaning of the point clouds (i.e., the process of deleting unwanted data from the scans).

The treated point cloud is then exported as a Plain Text Data Format (.ptx) file to MeshLab. This file contains multiple sets of coordinate triplets (X, Y and Z) as well as colour (RGB) and intensity values.

In MeshLab, the point cloud first undergoes a reduction in its number of points through the use of "Poisson-disk Sampling" [366] (Figure 34). This reduction eliminates points in areas of high point density (typically near the scan station position) while preserving points in low point density areas (typically farther from the scan station position). This first action results in more manageable point clouds, with smaller file sizes and fewer negative impacts on the computational power of the hardware without compromising relevant point cloud information. Afterwards, the algorithm "Screened Poisson Surface Reconstruction" [367] is applied to create a mesh from the remaining points (Figure 35). However, it should be stated that this algorithm may create surfaces that were inexistent in the initially scanned environment. As such, these surfaces must be removed through a semi-manual process using the proper selection algorithms available in MeshLab (Figure 36). Ultimately, before exporting the resulting mesh as an Object file (.obj), the point cloud colours must be transferred to their respective positions in the mesh surface. This relies on "Trivial Per-Triangle parametrization" and "Transfer: Vertex colour to texture" algorithms to map the entire mesh (securing the proper size and spacing of its triangles) and generate a Portable Network Graphics file (.png) containing the points' colours as a texture file. Figure 37 displays the acquired mesh before (left side) and after (right side) overlapping the created texture.

Figure 34 - Original point cloud (left); point cloud after reduction (right), adapted from [351].

Figure 35 - Mesh generation using the “Screened Poisson Surface Reconstruction” algorithm, adapted from [351].

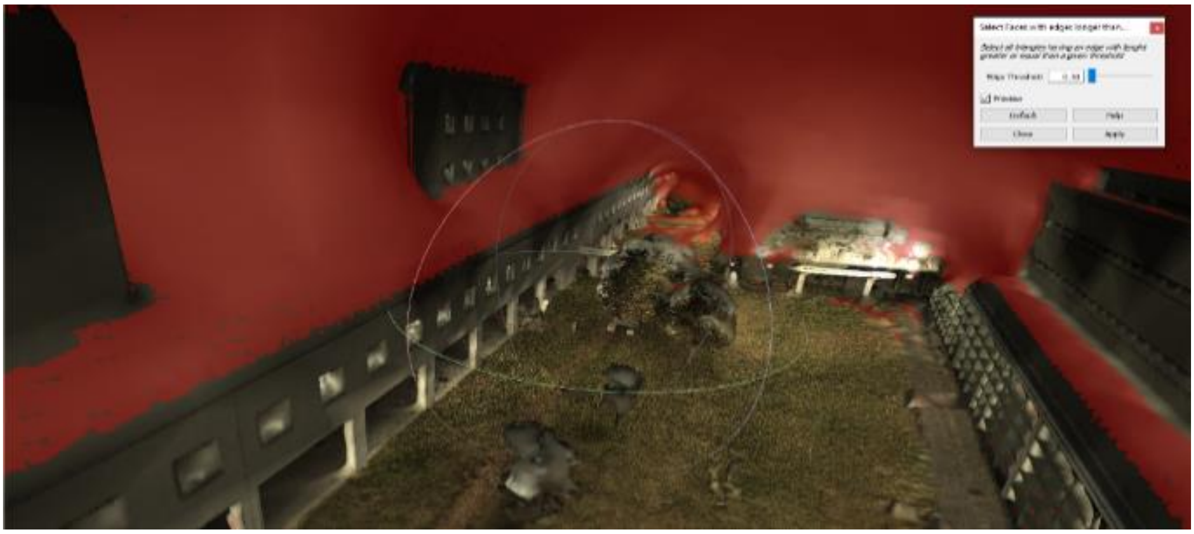

Figure 36 - Removing mesh segments that do not correspond to real scanned surfaces., adapted from [351].

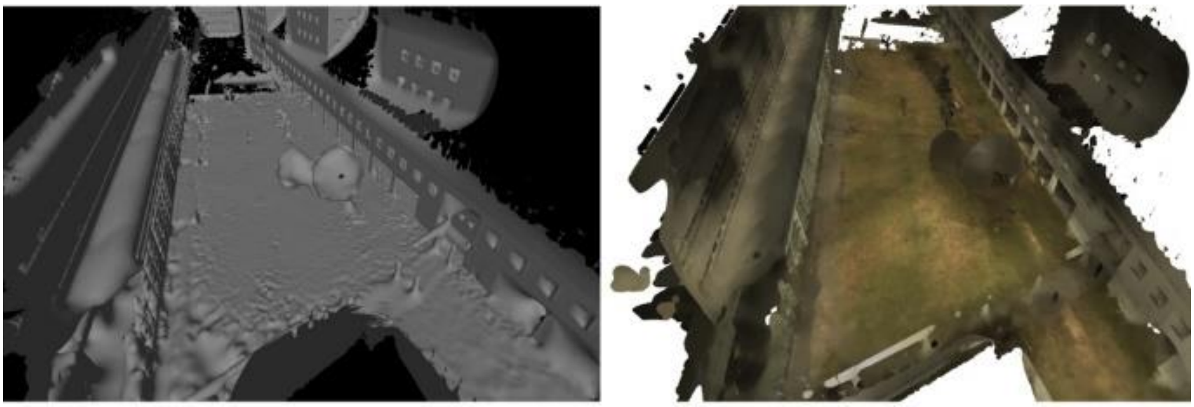

Figure 37 - Transferring vertex colours to the mesh: original mesh (left); resulting mesh after the process (right), adapted from [351].

4.2.2 Virtual Reality environment

The second step of the workflow concerns the development of the VR environment to provide an immersive scene where users can navigate, point to target building elements and add tags containing voice input information. The tags' position (i.e., x, y and z coordinates) and speech information are simultaneously recorded in a Text file (.txt).

The first step to achieving the immersive scene is to import the .obj and .png files as assets into a Unity 3D project. The .obj file contains the acquired mesh without colour information, while the .png file holds the created texture to overlap the .obj using UVW coordinates. The result consists of coloured meshes with textures arranged in the proper position (

Figure 38).

Figure 38 - Result within a Unity scene: meshes without colour information (left); coloured meshes with their respective textures (right), adapted from [351].

VR interactions were developed to allow the user to navigate the immersive environment and communicate with the project team by automatically providing information to be included in the BIM model. The locomotion technique uses teleportation mechanisms, which move the avatar to a target location by pressing and releasing one of the controllers' touchpads. The voice inputs are recorded using speech recognition functions [368] and, subsequently, pinned to a target mesh using a laser pointer (Figure 39). All interactions were developed to be handled using an HTC VIVE HMD and corresponding controllers.

Figure 39 - Placing annotations within the VR environment using voice inputs, adapted from [351].

4.2.3 BIM project update

In the third and last stage of the workflow, the .txt file containing the machine-interpreted results of the speech notes inserted by users and their respective 3D coordinates is exported from the VR interface to a Dynamo script. This script instantiates objects in a Revit project – family instances – containing the spoken notes as text strings, as depicted in Figure 39. The spheres are placed at the exact coordinates retrieved from the .txt file. To perform this step, Dynamo starts by retrieving all the information in the .txt file, creating an array of information. Only records containing machine-interpreted text from speech are selected for representation, while records with no text are discarded. Spheres are placed at the appropriate locations in the Revit project (Figure 40), and the text is added as a parameter.

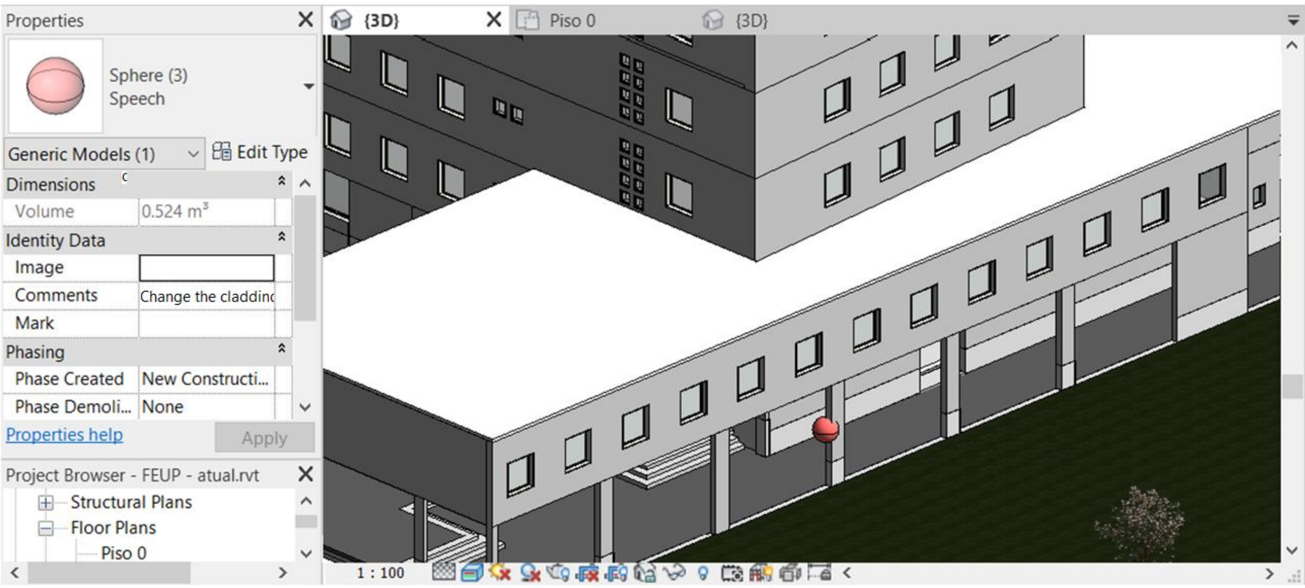

Figure 40 - Information sphere 3D representation as a family instance in a Revit project, adapted from [351].

A Dynamo interface was developed to support users in performing the last step of the workflow. As shown in Figure 41, the interface requires two inputs. The first is the location of the text file, while the second is the Revit family to be used. By default, the “Sphere” family is chosen.

However, this was left as an input option since users may select other BIM families for this purpose.

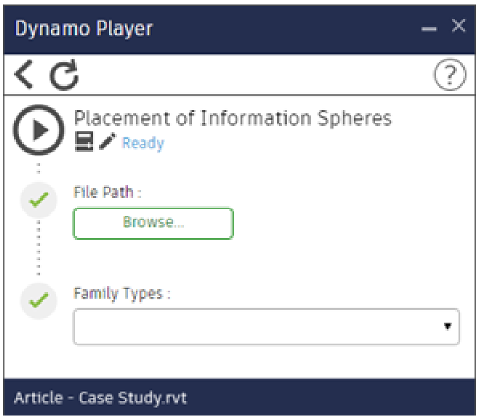

Figure 41 - Dynamo interface for the performance of the third step., adapted from [351].

As depicted in Figure 34 to Figure 41, preliminary laboratory tests were conducted, confirming that the interface corresponds to the original objectives of coupling laser scanning and VR– within a BIM environment – to improve communication in construction projects, update and enrich project information. Indeed, this proof of concept shows that the proposed system enables users to step into an immersive as-is virtual building environment and relay information (i.e., spoken strings of text) to the design team, thus enriching the associated BIM.

The workflow was tested using a VR-ready laptop (CPU: INTEL I7 – 6700HQ, RAM: 16GB DDR4, 256GB SSD, GPU: NVIDIA GTX 1060m) and an HTC VIVE HMD, in the Faculty of Engineering facilities at the University of Porto.

This prototype is a starting point for developing more complex NBIs for the semantic enrichment of BIM models, such as the one presented in the next section. It should be noted that these preliminary tests were merely focused on the runnability of the system rather than the usability assessment of the proposed solution.

The following section describes the development and validation of a second interface, including a thorough usability assessment procedure.

4.3 NBI for Semantic Enrichment — Workflow Overview

The system architecture of the proposed solution for semantic enrichment comprises two fundamental components and one complementary module:

i) a Python module, i.e., a custom widget developed to provide a straightforward openBIM approach to import BIM models into a game engine while maintaining models' semantics and geometry. This module also updates the original IFC file automatically to match changes made in the immersive VR environment by the end-users. Furthermore, the Python module provides validation of new information added to the BIM model through the use of IDS. IfcOpenShell (open-source Python toolkit) [189] was used to develop features to parse, convert, and validate IFC files; and

ii) a Unity module comprising a VR immersive interface to access and edit BIM non-geometric information through the use of gesture and voice commands.

The complementary module encompasses a C-Sharp (C#) script using the xBIM toolkit (open-source) [369] so that the final updated IFC file can be converted to COBie spreadsheets.

An overview of the entire workflow is exposed in Figure 42. Additionally, the workflow is designed for two types of users, designers and BIM technicians (users type 1 – UT1), and buildings' facility management operational staff (users type 2 – UT2). UT1 are responsible for preparing the model to meet the requirements to be imported into the game engine. The preparation entails creating a JSON file with the necessary information to be accessed by UT2 and converting the IFC file to COLLADA (.dae) so that the geometry and materials of the BIM model can be maintained within a Unity scene. This phase is henceforth identified as the *Preparation Phase*. Afterwards, UT2 are tasked with editing the required building elements' semantic information according to work carried out on-site and to information specifications. This phase is designated as the *End-User Phase*.

The last phase, the *Validation Phase*, regards changes made to building elements' data within the VR environment using the Python widget and according to the exchange requirements defined in a custom IDS.

Overall, the proposed solution requires three phases:

i) Preparation phase – performed by UT1;

ii) End-user phase – performed by UT2; and

iii) Validation phase.- performed by UT1.

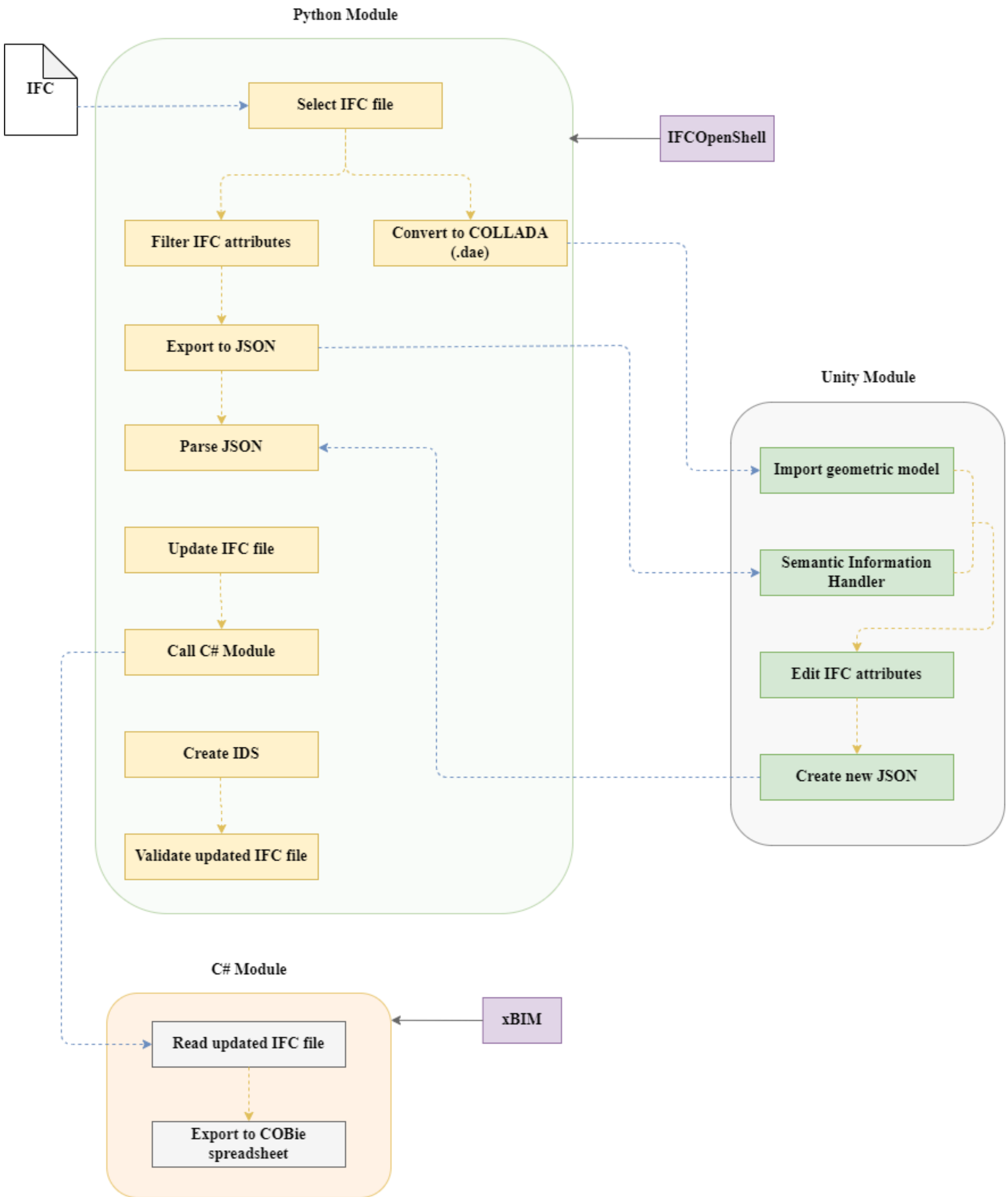

Figure 42 - System overview.

4.3.1 Preparation Phase

The *Preparation Phase* comprises a two-step process consisting of adjusting the geometric and semantic data of the BIM model to be imported into the game engine (i.e., Unity module). COLLADA and JSON files are created by UT1, acting as the entry point of the workflow (Figure 42). In detail, the two-step process includes two main actions:

i) Converting the geometry of the model; and

ii) Preparing the JSON file containing the model semantics (a subset of the original IFC file).

Figure 43 provides a breakdown of the steps comprising the *Preparation Phase*.

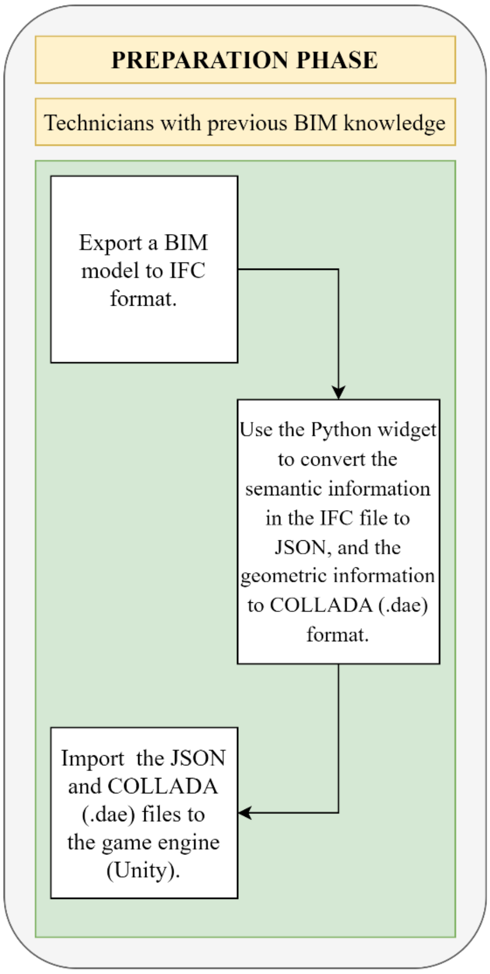

Figure 43 - Outline of the steps comprising the *Preparation Phase*.

The model's geometric information is converted using a Python widget by UT1, selecting the "IFC to COLLADA" button, as depicted in Figure 44.

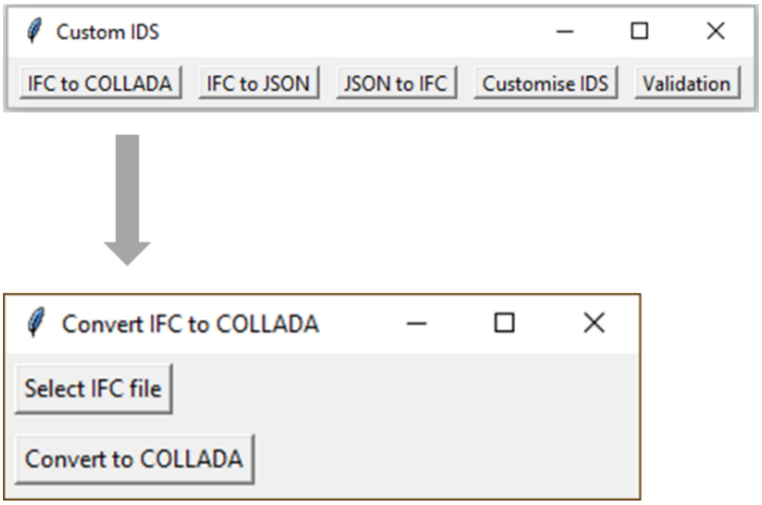

Figure 44 - Python Widget - Conversion of IFC files to COLLADA.

The conversion process uses IfcConvert, an IfcOpenShell library wrapper, to convert the file to .dae file format. Additionally, the process is set to keep the GlobalId attribute of each building element instead of the element's name. This feature allows the workflow to be independent of BIM authoring tools' namings for building elements which may result in non-unique names. Therefore, using GlobalIds as an alternative provides a straightforward approach to matching corresponding non-geometric information, ensuring that most geometry and materials of the IFC file are preserved throughout the conversion and import of the .dae file into Unity (Figure 45).

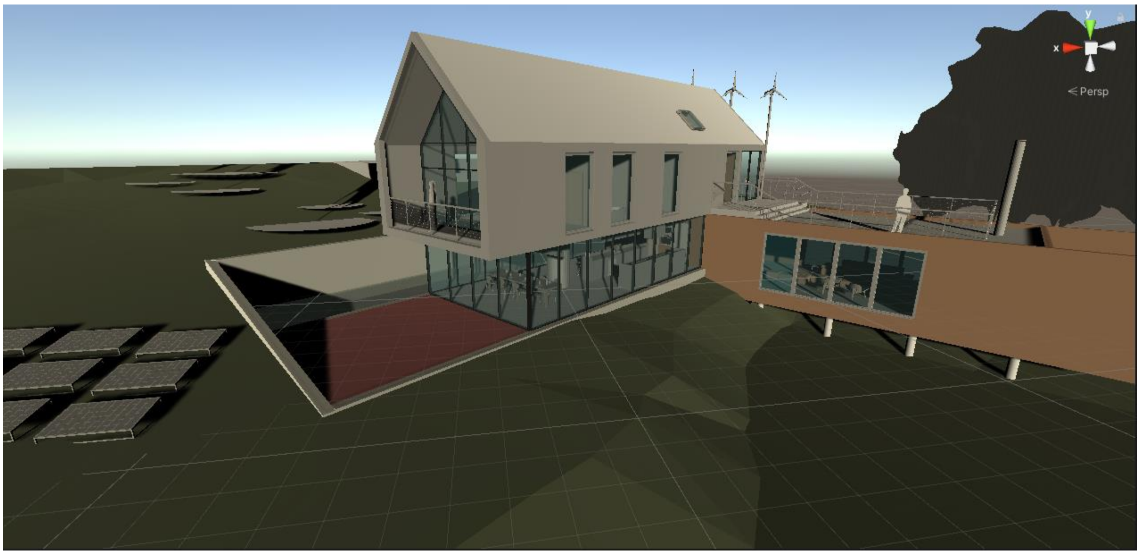

Figure 45 - Resultant COLLADA (.dae) file imported into Unity game engine.

Regarding the process of importing the model semantics (non-geometric information) to the game engine, UT1 filter the initial IFC into a subset of its entities by selecting the Python widget's "IFC to JSON" option (Figure 46). In detail, the IFC schema is reduced to a number of elements hierarchically related by type, i.e., a subset of a chosen "IFC type class" entity [370] (e.g., IfcProduct, IfcBuildingElement), and then converted to the JSON format (Figure 47).

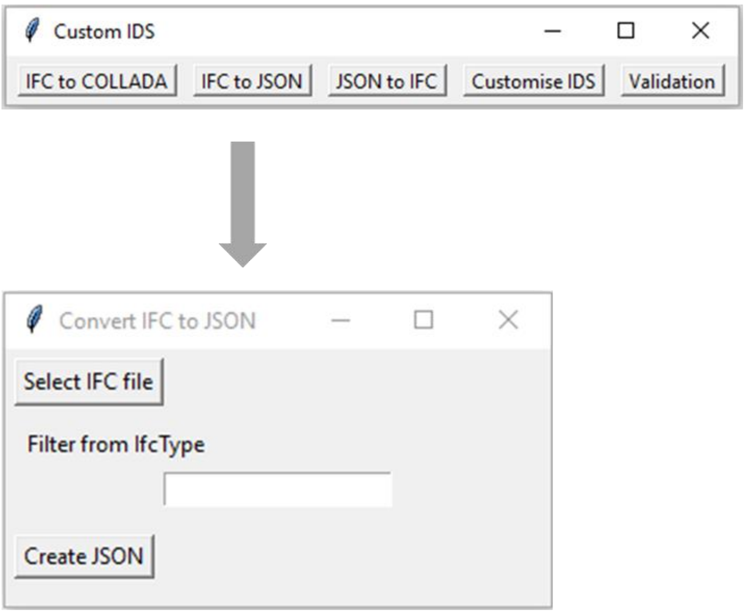

Figure 46 - Python Widget – Conversion of IFC files to JSON data format.

Afterwards, the JSON file is imported into Unity and stored in the streaming assets folder. The game engine links the data with the corresponding building elements using C# scripts as soon as the virtual environment (i.e., scene) is instantiated. Also, all building elements must have an IFC file tag so that handlers (C# scripts) can identify those 3D objects.


```
▼ object {2}
  ▶ schema {3}
  ▼ data [400]
    ▼ 0  {20}
         index : 0
         id   : 6676
         type : IfcSlab
         GlobalId : 0WFFycJ9rEj9FbADAA0q3o
         OwnerHistory : #41=IfcOwnerHistory(#38,#5,$,.NOCHANGE.,$,$,$,1645543215)
         Name : Floor:Generic 150mm:176804
         Description : null
         ObjectType : Floor:Generic 150mm
         ObjectPlacement : #6643=IfcLocalPlacement(#150,#6642)
         Representation : #6674=IfcProductDefinitionShape($,$,(#6672))
         Tag  : 176804
         PredefinedType : FLOOR
         ShapeType : null
         OverallHeight : null
         OverallWidth : null
         CompositionType : null
         NumberOfRiser : null
         NumberOfTreads : null
         RiserHeight : null
         TreadLength : null
    ▼ 1  {20}
         index : 1
         id   : 6807
         type : IfcWallStandardCase
         GlobalId : 3lLx0gNe59vvExhby0Bfew
         OwnerHistory : #41=IfcOwnerHistory(#38,#5,$,.NOCHANGE.,$,$,$,1645543215)
         Name : Basic Wall:SIP 202mm Wall - conc clad:198694
         Description : null
         ObjectType : Basic Wall:SIP 202mm Wall - conc clad
         ObjectPlacement : #6763=IfcLocalPlacement(#162,#6762)
         Representation : #6805=IfcProductDefinitionShape($,$,(#6769,#6803))
         Tag  : 198694
```


Figure 47 - Example of a portion of a JSON file after conversion.

4.3.2 End-User Phase

The *End-User Phase* is designed to be performed by operational staff (i.e., UT2) with years of practical experience in on-site maintenance work, although usually lacking the technical knowledge to convey on-site operations information directly to a BIM authoring tool. Figure 48 shows the core actions of this phase.

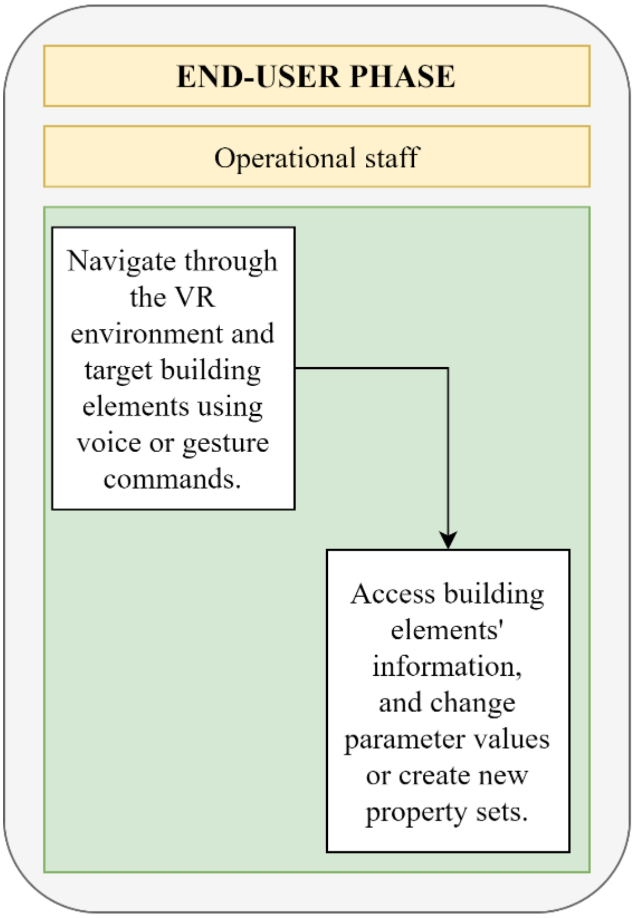

Figure 48 - Main steps included in the *End-User Phase*.

An approach based on voice commands and gestures was developed to avoid excluding UT2 from the BIM information exchange, providing alternative means of interaction with building information in an immersive environment (Figure 49). This NBI provides access to the building elements' data and allows the option to change parameters or create new property sets, as shown in Figure 50 to Figure 52. Changes are saved as new JSON files, which are sent to UT1 to update the original IFC file through the Python widget and proceed with the *Validation Phase*.

Figure 49 - Interaction with the VR interface — *End-User Phase*.

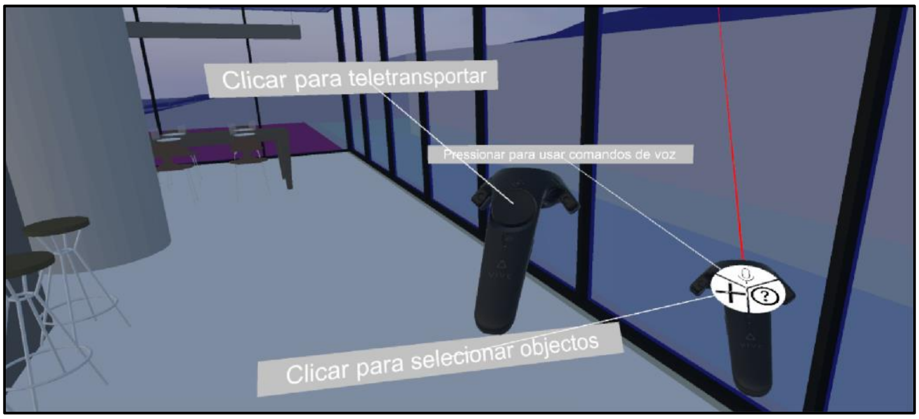

Figure 50 – Interactions available within the NBI: teleport, object selection, and voice commands

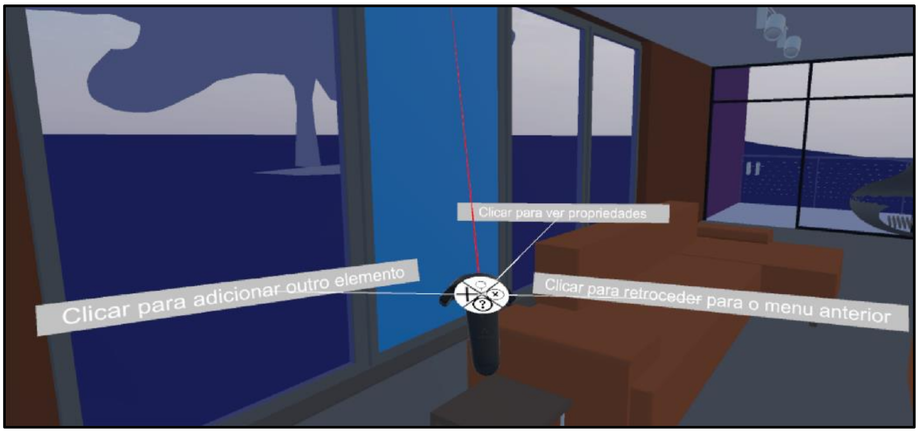

Figure 51 – Interactions available within the NBI: multiple object selection and display of IFC attributes

Figure 52 - Building elements' IFC attributes displayed in the immersive virtual environment and the option to create new property sets.

4.3.3 Validation Phase

The last phase entails the update of the original IFC file as well as the conversion to a COBie spreadsheet (xBIM toolkit). This step entails using the Python widget to automatically parse the JSON file - output of the NBI (*End-User Phase*) - to update the original IFC.

Moreover, the option to conduct file validation against a user-defined IDS is available during this stage. An overview of this stage is depicted in Figure 53

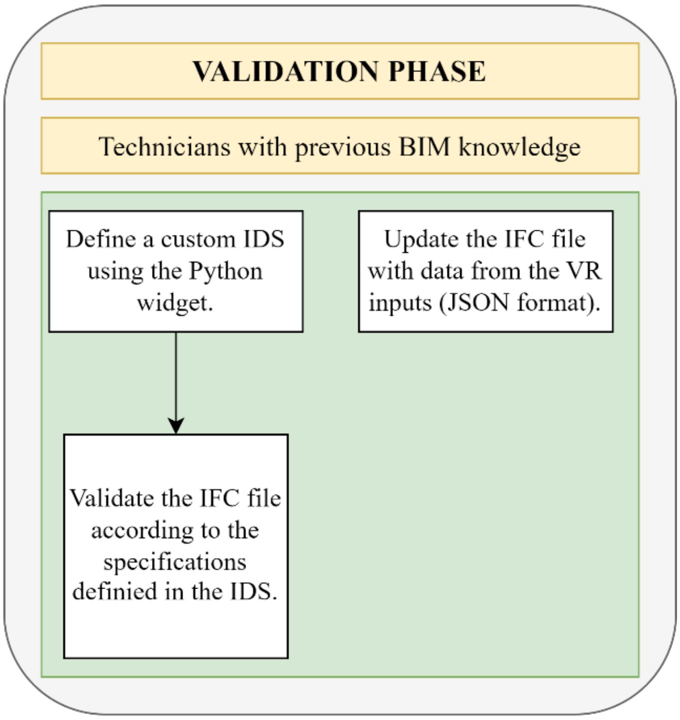

Figure 53 - Summary of the steps included in the *Validation Phase*.

The validation is carried out by first defining a custom IDS through the Python widget by choosing the option "Customise IDS", as shown in Figure 54. This step requests the specification of applicable entities and requirements to validate the IFC file. These may include names of building elements' entities and parameters (e.g., user-defined property sets) and their expected or required values, as seen in Figure 54 and Figure 55.

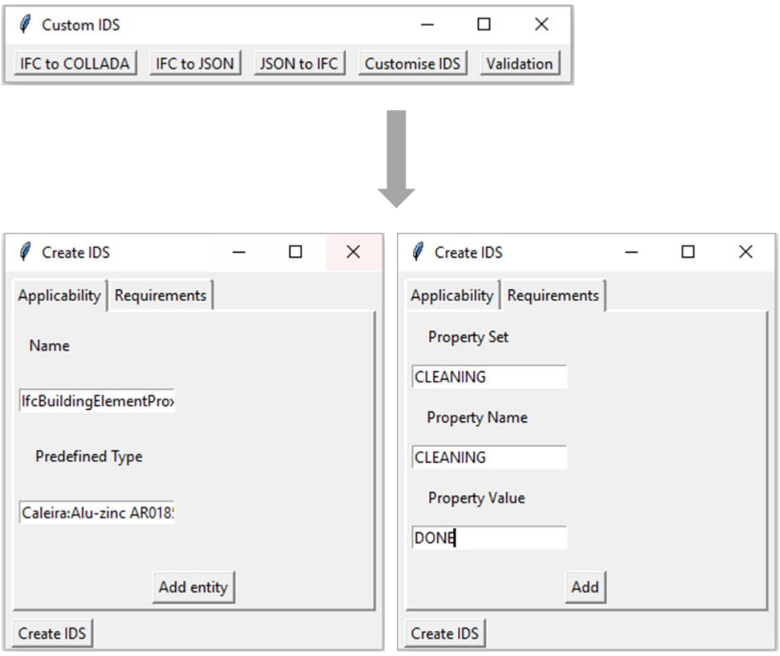

Figure 54 - Specification entities and parameters (exchange requirements) to be validated through an IDS.


```xml
<?xml version="1.0" encoding="UTF-8"?>
<!-- IDS (INFORMATION DELIVERY SPECIFICATION) CREATED USING IFCOPENSHELL -->
<ids xmlns="http://standards.buildingsmart.org/IDS" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    <specification name="Test_Specification 0" necessity="required">
        <applicability>
            <entity>
                <name>
                    <simpleValue>IfcBuildingElementProxy</simpleValue>
                </name>
                <predefinedtype>
                    <simpleValue>Caleira:Alu-zinc AR0185</simpleValue>
                </predefinedtype>
            </entity>
        </applicability>
        <requirements>
            <property location="any">
                <propertyset>
                    <simpleValue>CLEANING</simpleValue>
                </propertyset>
                <name>
                    <simpleValue>CLEANING</simpleValue>
                </name>
                <value>
                    <simpleValue>DONE</simpleValue>
                </value>
            </property>
        </requirements>
    </specification>
    <info>
        <date>2022-07-22</date>
    </info>
</ids>
```


Figure 55 - Example of the structure of a custom IDS (XML format).

Simultaneously, the original IFC file is updated with the properties edited in the immersive environment. Figure 56 exhibits a 3D view of the updated IFC file using a free model viewer.

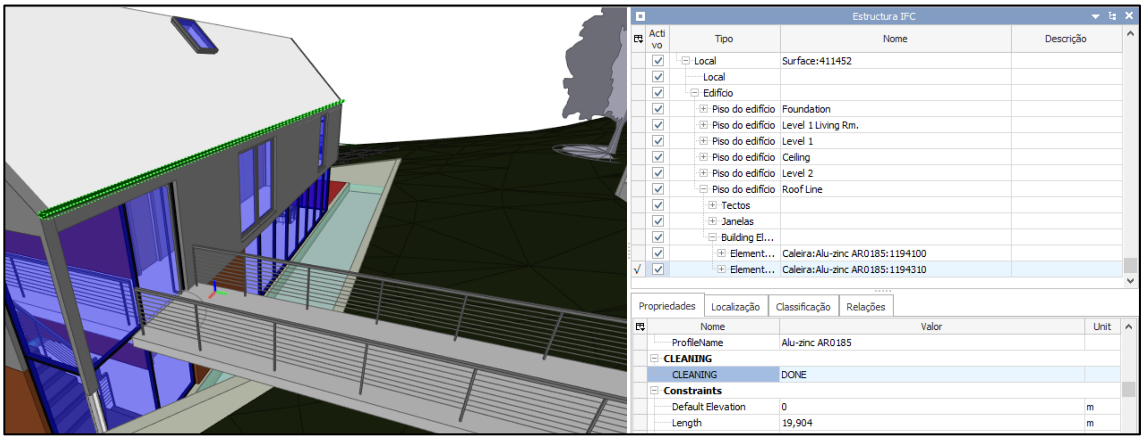

Figure 56 - 3D view of the updated IFC file.

After defining parameters and corresponding values for the custom IDS, the updated IFC file is automatically verified, and reports are issued in text and BIM Collaboration Format (BCF) files. These files enable the verification of building elements' compliance with the users' (UT1) previously defined specifications.

Figure 57 demonstrates the compliance status of different building elements based on the predefined IDS.

logFromWidget.txt

```
{'guid': '2PxJ01pBfA8xp9W7$qYM22', 'result': True, 'sentence': "Given an instance with an entity name 'IfcBuildingElementProxy'\nWe expect anyproperty 'CLEANING' in 'CLEANING' with a value DONE.\nIfcBuildingElementProxy 'Caleira:Alu-zinc AR0185:1194310' (#927148) has a property 'CLEANING' in 'CLEANING' with a value 'DONE' so is compliant", 'ifc_element': #927148=IfcBuildingElementProxy('2PxJ01pBfA8xp9W7$qYM22',#41,'Caleira:Alu-zinc AR0185:1194310',$,'Caleira:Alu-zinc AR0185',#927147,#927142,'1194310',$)}
{'guid': '3jrUqJSoP4aggxh17Ae7tm', 'result': False, 'sentence': "Given an instance with an entity name 'IfcBuildingElementProxy'\nWe expect anyproperty 'CLEANING' in 'CLEANING' with a value DONE.\nIfcBuildingElementProxy 'EPW305' (#927457) has does not have a set 'CLEANING' so is not compliant", 'ifc_element': #927457=IfcBuildingElementProxy('3jrUqJSoP4aggxh17Ae7tm',#41,'EPW305',$,'Electrical_Distribution:EPP-W304',#927456,#927451,'1202517',$)}
{'guid': '0Qn0xDcrP0Ie69cIIE3wtB', 'result': False, 'sentence': "Given an instance with an entity name 'IfcBuildingElementProxy'\nWe expect anyproperty 'CLEANING' in 'CLEANING' with a value DONE.\nIfcBuildingElementProxy 'Walvit_Hung Bowl_604118 W:Walvit:499496' (#87099) does not have a set 'CLEANING' so is not compliant", 'ifc_element': #87099=IfcBuildingElementProxy('0Qn0xDcrP0Ie69cIIE3wtB',#41,'Walvit_Hung Bowl_604118 W:Walvit:499496',$,'Walvit_Hung Bowl_604118 W:Walvit',#87098,#87093,'499496',$)}
{'guid': '1RUi90wQT3ihQ$96bMNGp7', 'result': False, 'sentence': "Given an instance with an entity name 'IfcBuildingElementProxy'\nWe expect anyproperty 'CLEANING' in 'CLEANING' with a value DONE.\nIfcBuildingElementProxy 'water:water:628359' (#93214) does not have a set 'CLEANING' so is not compliant", 'ifc_element': #93214=IfcBuildingElementProxy('1RUi90wQT3ihQ$96bMNGp7',#41,'water:water:628359',$,'water:water',#93213,#93208,'628359',$)}
{'guid': '29jzdd0Ab5sOIOupfzx1Ur', 'result': False, 'sentence': "Given an instance with an entity name 'IfcBuildingElementProxy'\nWe expect anyproperty 'CLEANING' in 'CLEANING' with a value DONE.\nIfcBuildingElementProxy 'Miele Washing Machine W 5820 WPS:Miele Washing Machine W 5820 WPS:674370' (#102994) does not have a set 'CLEANING' so is not compliant", 'ifc_element': #102994=IfcBuildingElementProxy('29jzdd0Ab5sOIOupfzx1Ur',#41,'Miele Washing Machine W 5820 WPS:Miele Washing Machine W 5820 WPS:674370',$,'Miele Washing Machine W 5820 WPS:Miele Washing Machine W 5820 WPS',#102993,#102988,'674370',$)}
```

Figure 57 – Automatic report of the compliance status of different building elements based on the custom IDS.

4.4 NBI for Semantic Enrichment — Usability Assessment

The usability assessment of the proposed interface for semantic enrichment was subject to two different evaluation stages, according to the proposed evaluation methodology introduced in section 3.5:

i) Formative evaluations during the early development stage to gather feedback from experts concerning possible usability issues;

ii) A second evaluation — summative evaluation — during the near-finished development stage, including the selection of usability domains and definition of goal lines. Furthermore, qualitative methods were also considered by gathering data from semi-structured interviews.

The hardware used to conduct the tests included a VR-ready laptop (CPU: INTEL I7 – 6700HQ, RAM: 16GB DDR4, 256GB SSD, GPU: NVIDIA GTX 1060m) and an HTC VIVE HMD.

Figure 58 summarises the two main stages of the usability assessment.

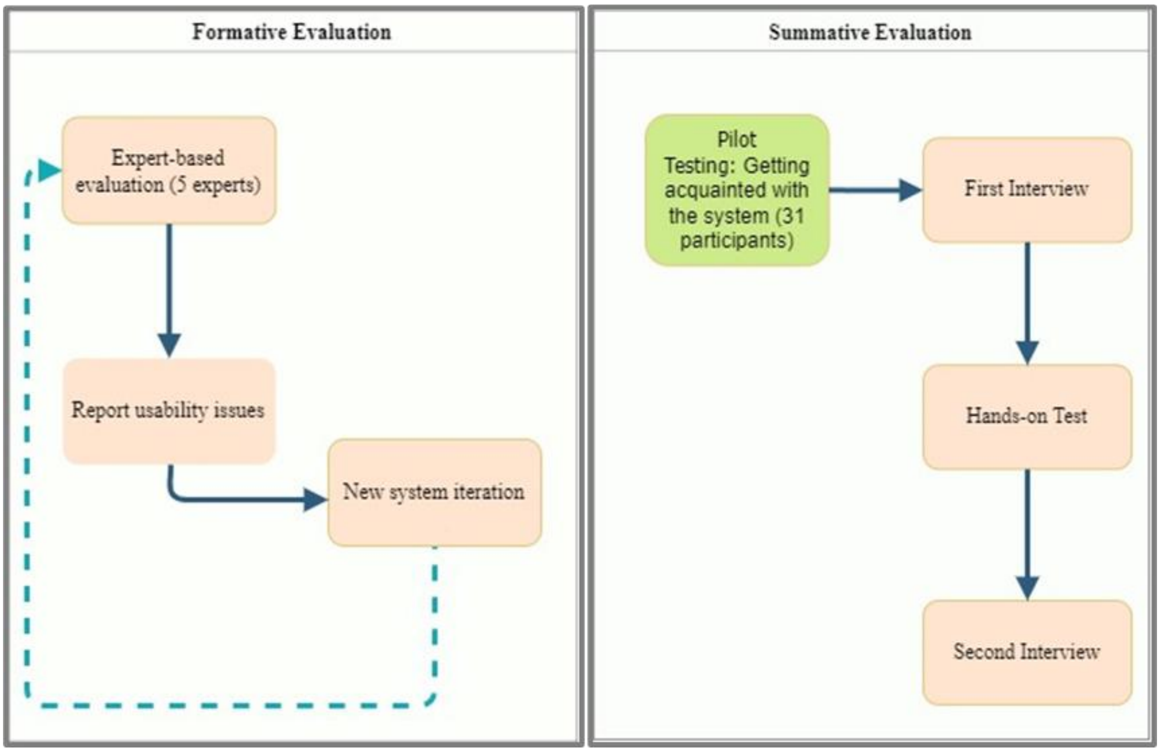

Figure 58 - Usability assessment procedure.

4.4.1 Formative Evaluations

As asserted by Benyon [275], usability evaluations may be divided into two approaches: participant-based and expert-based methods.

Expert-based evaluations rely on a set of specialists in HCI or usability to test a development version of an interface. These specialists should draw on their experience to assess the interface against general design principles, i.e., heuristics [275]. This approach is also known as formative evaluation and is generally carried out during the early phases of development, where significant changes affecting the system may still be pointed out [275]–[277].

According to Nielsen [276], three to five evaluators accomplish a balance between a manageable group of experts and the number of problems that may be found during their assessment. In this regard, five experts were selected to assess the proposed interface during the early stages of development, ensuring that most usability problems were identified before the participant-based evaluations (i.e., summative evaluations). In detail, the group of experts comprised two usability professionals, two informatics engineers, and 1 BIM researcher. The formative evaluation consisted in testing the interface by completing a set of 3 previously established tasks:

i) go to the living room, select the fireplace, and identify the object's properties;

ii) select all slabs using voice controls and create a new property set;

iii) select a glass door using the virtual laser pointer and change the object's height and length values.

Nielsen's ten usability heuristics [371] were used so that each expert could classify as many usability problems as possible. From the collected feedback, 13 usability issues were highlighted during the formative evaluations, which were revised later in the system. Most problems concerned "recognition rather than recall", "help and documentation", "user control and freedom", and "visibility of system status" based on [371].

4.4.2 Summative Evaluations

The second approach employed in this study, summative evaluation, is intended for near-finished products [277], so the overall quality of the interfaces may be assessed [276] by the intended users (i.e., participants). During summative evaluations, measurement tests become appropriate to consider previously outlined usability attributes. As contended by Sauro and Kindlund [289], to perform a summative evaluation of the usability of a product, it is required to define and measure a set of metrics. The assessment of usability attributes or domains (e.g., efficiency, effectiveness, satisfaction, memorability, learnability, and safety, among others) may comply with international standards and recommendations. This study is consistent with the view of ISO 9241-11 [287] and ANSI INCITS 354-2001 [288], which define the dimensions of usability as composed of efficiency, effectiveness and satisfaction. Furthermore, the present study is aligned with the definitions and guidelines introduced in section 3.4 and section 3.5.

During the summative evaluations, users were expressly informed about the tasks to be performed during the individual test. As effectiveness and efficiency are usability domains related to task definition, this study considered effectiveness as the completion rate of tasks (percentage) and Efficiency as the time used to complete each task (seconds). Moreover, assuming that each user intends to complete the established tasks, in the event of failure or non-completion of a given “sub-task”, a penalty should be imposed on the completion rate, i.e., a percentage is deduced to the overall task completion rate [289].

Regarding the satisfaction domain, various questionnaires may be used (e.g., System Usability Scale (SUS) [372], Software Usability Measurement Inventory (SUMI) [373], Post Study System Usability Questionnaire (PSSUQ) [374]). The SUS [372] is a well-established tool and has the advantage of being relatively short (i.e., ten questions), with proven reliability [375] (see also[294]). It is also relatively easy to analyse the results. A European Portuguese adaptation of the SUS was employed in agreement with Martins et al. [376] to ensure that all users could fully understand each question.

All participants' questionnaires were rated using a five-point Likert scale to obtain the SUS score. That is, the values of the answers must be adapted according to the question order so that answers to odd-numbered items are subtracted one value, and each response to an even-numbered item will have its rating deducted from five. After adding the values of each answer, the resulting sum should be multiplied by 2.5 [294], obtaining a score between 0 and 100 (percentage).

Although more commonly used in the Social Sciences and Humanities [377], [378], a qualitative approach was deemed necessary to support the present study and provide a further understanding of the perceived utility of the developed VR solution. The option to use interviews as a data collection technique was based on four fundamental reasons:

i) the fact that it is based on the interviewees' discourse [379], [380];

ii) because it is based on verbal and dynamic one-to-one communication [379], [380];

iii) for it provides information on specific research topics directly with key informants [379], [380]; and

iv) for the possibility of establishing direct contact with the interviewees [379], [380].

Two semi-structured interviews were conducted to guarantee that the users' (i.e., construction management professionals and operational staff) perceptions and opinions were documented: one before testing the proposed VR system; another immediately after the hands-on test. The semi-structured interviews entailed developing a structured script comprising predetermined topics, dimensions, and questions identified as paramount to meet the research questions and objectives of this study. Additionally, the script acted as a tool to be addressed throughout the interviews as a reference and when the interviewer considered the need for steering the conversation to meet all planned topics and questions (although not necessarily in the defined order of the script) and to arouse the interviewee's interest [381]–[383]. Furthermore, this process always respected the moments of discourse and the interviewee's thoughts without ignoring the script [381]–[383].

Before all the interviews were conducted, participants read and signed an informed consent form to ensure the privacy, confidentiality and anonymisation of the data to be shared [384] (

Appendix II).

A total of 62 interviews were conducted with 31 AECO professionals, 31 pre-test interviews and 31 post-test interviews between March and May of 2022. It should be noted that both the interviews and the VR hands-on (summative evaluation) were conducted on the same day, i.e., the first interview was performed, followed by the proposed interface test and, finally, the second interview. This procedure allowed insight into the participants' pre-and post-test knowledge and utility perceptions concerning the VR interface.

All participants in the interface assessment stage were facility management professionals with different academic backgrounds from eight Higher Education Institutions (HEIs), one research institution, one science and technology park, and 2 AECO sector companies. The sample size was determined based on Montgomery et al. [385], that contend that for practical cases, a sample size with a sample size (N) equal to or higher than 30 will conform with a normal distribution.

In the present study, the sample comprises 9,7 % female and 90,3 % male participants. Ages range from 30 to 63 years old. Ten participants were 30 to 40 years old, 13 were between 41 and 50, 5 were between 51 and 60, and the remaining three were aged between 61 and 63. Considering the academic background, 41,9% of the participants hold higher education degrees, and the remaining participants (58,1%) have primary to high school education levels, a technical or professional degree. Table 16 presents an overview of all the participants' profiles (i.e., age, academic background, and sex).

Table 16 - Overview of the participants' profiles.

Number	Age	Academic Background	Sex
1	61	8th grade	M
2	46	9th grade	M
3	53	Graduate in Civil Engineering	F
4	52	Bachelor in Civil Engineering	M
5	34	Graduate in Civil Protection	M
6	62	4th grade	M
7	43	12th grade	M
8	46	Graduate in Informatics Engineering	M
9	48	Graduate in Education Science	M
10	49	9th grade	M
11	31	Higher Education Student	M
12	42	Professional course	M
13	32	9th grade and a professional course in Electricity	M
14	32	12th grade	M
15	53	4th grade	M
16	40	Degree in Civil Engineering and a postgraduate course	M
17	50	Degree in Electrical Engineering	F
18	47	6th grade	M
19	46	Degree in Mechanical Engineering	F
20	51	Degree in Electrical Engineering	M
21	63	12th grade	M
22	37	12th grade	M
23	41	9th grade	M
24	30	Master in Electrical Engineering	M
25	45	9th grade	M
26	56	6th grade	M
27	46	12th grade	M
28	41	12th grade	M
29	38	Degree in Mechanical Engineering	M
30	34	Professional course	M
31	34	Degree in Civil Engineering	M

After conducting the 62 interviews, they were transcribed, ensuring the anonymisation of the participants' personal data. Also, the institutions where participants work will not be identified. Instead, only references to these institutions' context of action will be made available, e.g., HEIs, or AECO companies.

All transcribed documents were systematised and analysed using the qualitative data analysis software Nvivo, version 12, based on content analysis as a data-processing technique [386]. This software was used to create a categorical tree with three "mother/main" categories and 17 subcategories prior to the analysis process. In other words, categories were previously developed by the authors based on the theoretical framework of this study, the research objectives, and the script developed for the interviews [387]–[389].

The summative evaluation included an initial interview, followed by a five-minute trial to get acquainted with the hardware in an immersive scenario. Afterwards, each participant was requested to complete a series of four tasks, as detailed in Table 17, without the help of the researcher guiding the test. The only information available to the participants was the description of each task and subtasks (read by the researcher on participants' demand), with no further indication on how to proceed.

Table 17 - Task description.

Task description	
1	**Checking a domestic electrical switchboard**
1.1	Move to the object
1.2	Select the object
1.3	Open the object properties panel
1.4	Select the property: "Name"
1.5	Write a new property value: "New board"
1.6	Save
2	**Checking the state of two gutters**
2.1	Move to the object
2.2	Select the object
2.3	Open the object properties panel
2.4	Create a new Property Set
2.5	Select the button to edit the Property Set name
2.6	Edit the Property Set name to: "Cleaning"
2.7	Select the button to edit the Property Set value
2.8	Edit the Property Set value to: "Done"
2.9	Save
2.10	Move to the second gutter
2.11	Repeat tasks 2.2 to 2.9
3	**Checking all taps**
3.1	Move to floor 0
3.2	Use the voice command to select all taps
3.3	Select the button to create a new Property Set
3.3	Select the button to edit the name of the Property Set
3.4	Edit the name of the Property Set to: "Is working"
3.5	Select the button to edit Property Set value
3.6	Edit the value of the property set to: "O.K."
3.7	Save
4	**Checking the kitchen tap**
4.1	Move to the object
4.2	Select the object
4.3	Open the object properties panel
4.4	Select the button to create a new Property Set
4.5	Select the button to edit the name of the Property Set
4.6	Edit the name of the Property Set to: "Is working"
4.7	Select the button to edit Property Set value
4.8	Edit the value of the property set to: "K.O."
4.9	Save

All participants had 60 minutes to complete the practical part (i.e., hands-on test), starting with a 5-minute trial to get acquainted with the hardware and virtual environment, followed by approximately 55 minutes to complete tasks one to four. Each participant replied to the SUS questionnaire upon completing all tasks, exceeding the 60-minute mark, or withdrawing from the test. The summative evaluation ended with a post-test interview.

4.4.3 Results

The data elicited after completing the interface evaluation process shows that five participants had previous experience with BIM. In turn, 26 participants stated they did not know about BIM before taking the test (i.e., the summative evaluation). Another noteworthy aspect is previous experience with VR equipment. In this regard, ten participants reported some previous experience, whereas 21 had their first experience with immersive VR equipment during the test session. All participants had a five-minute trial to become used to the HTC VIVE head-mounted display before testing the actual interface. This trial is required in this case, as most users had no expertise with immersive VR, which is different from most traditional non-immersive interfaces (e.g., flat screens). This preliminary trial scene consisted of the same immersive environment to be tested afterwards but with no functionality besides visualisation. This phase allowed inexperienced users to become acquainted with the hardware and the immersive environment, which is consistent with Nielsen [276] concerning transitions between technologies and interfaces and the need to ensure that the test results would not be biased by an excessive effort from the users interacting with the interface mechanics.

The test results show that from a total of 31 participants, eight did not complete the test (25, 8%), and 23 users (74,2%) completed the test with 100% effectiveness.

It was necessary to perform a scale transformation according to the guidelines mentioned in section 3.5, considering that the Efficiency attribute is measured on a time scale (e.g., the number of seconds spent performing a task), while the others are assessed on a percentage scale between 0 and 100. In this sense and considering the inexistence of a general rule to establish the duration of tasks (to the author's best knowledge), an acceptable target time range, minimum and maximum values were outlined for each task. This procedure distinguishes the target time for different efficiency ranges and transforms each participant's task completion time into a corresponding Efficiency percentage value. Based on a similar approach to Nielsen [276] and Rideout [390], two usability goal lines were prepared, as depicted in Figure 59.

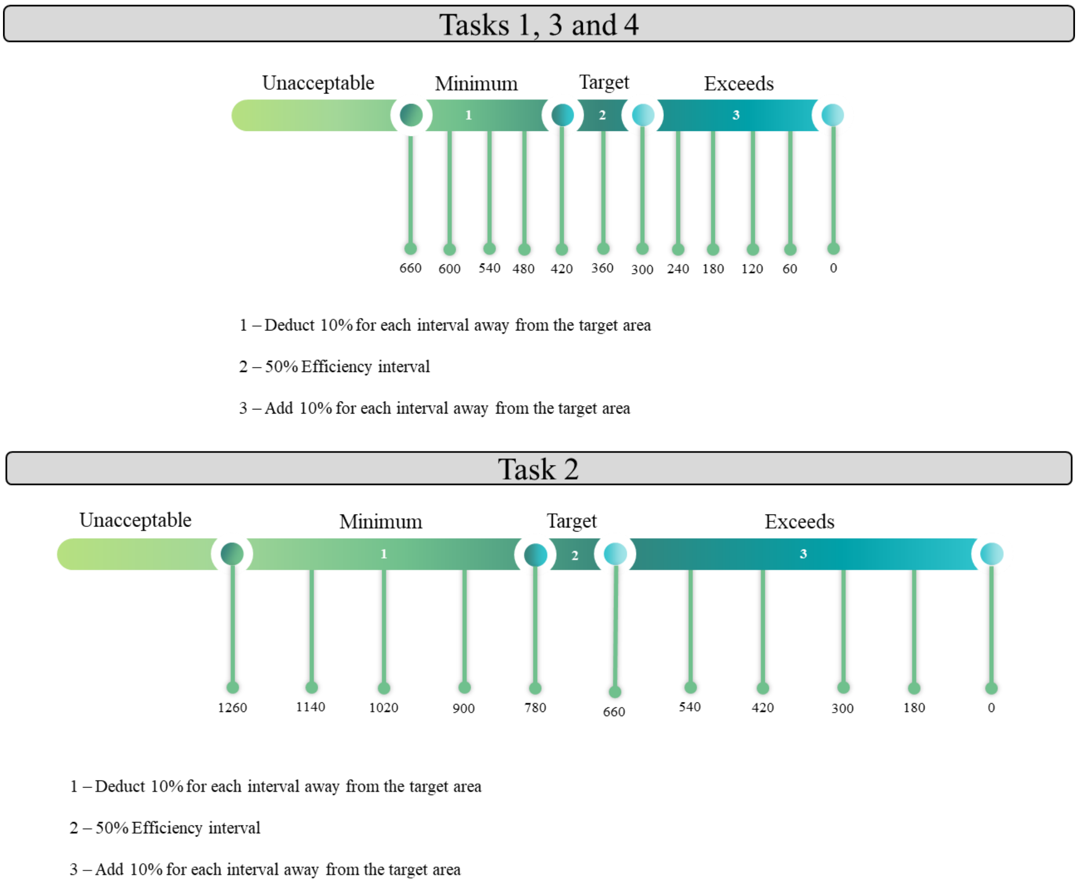

Figure 59 - Usability goal lines used for the scale transformation of the Efficiency attribute.

Figure 60 shows an increase in efficiency over the test duration. Indeed, the data indicates a higher number of participants with 0% efficiency in Task 1 (12 occurrences), following a decreasing number of occurrences in Task 2 (nine occurrences), and a smaller amount still in Tasks 3 and 4 (eight occurrences). This behaviour may be explained by the authors' intention not to provide prior instructions on how to interact with the system, hence to better assess how participants interacted with the system without knowing which commands and operations were available to meet the objectives of each task. As such, lower efficiency values were expected during the first task.
Conversely, Figure 60 indicates that higher efficiency levels were progressively verified throughout the test. Indeed, 14 participants scored 50% and above in the first task, 21 in Task 2, 23 in Task 3, and 21 in Task 4. Additionally, Task 4 verified 67,7% of users with efficiency levels over 80% and above. These results suggest that the participants learned how to use the system while performing tasks in the virtual environment.
Hence, it is possible to ascertain that participants were able to interact with BIM information in a natural way using the proposed system. Indeed, most participants reached an efficiency level close to that expected for users familiar with the interface (i.e., high-efficiency values), especially on Tasks 3 and 4.

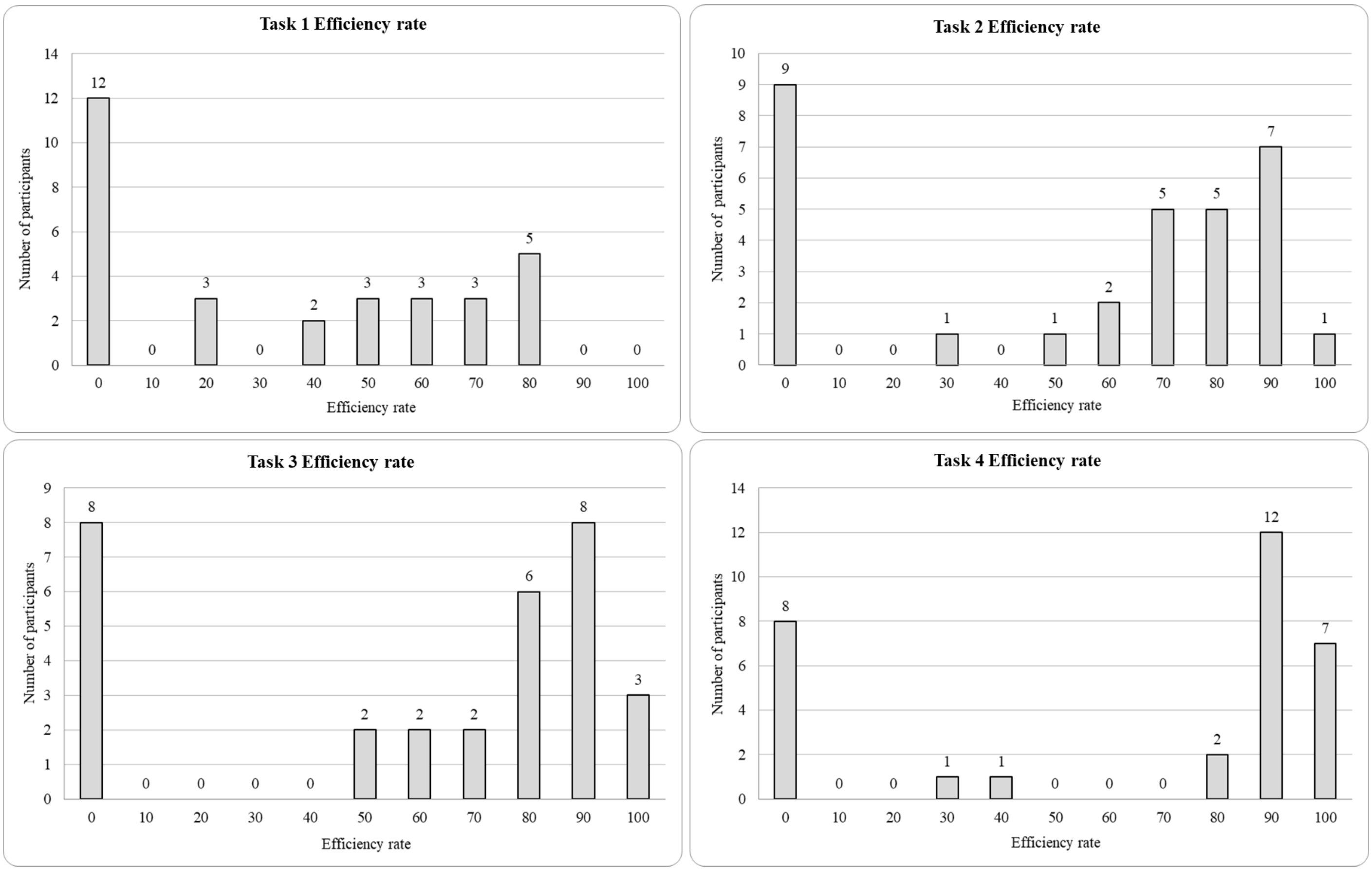

Figure 60 - Task efficiency rate.

Concerning the perceived satisfaction of the proposed interface, most participants (64,5%) scored above 68 (i.e., results from answers to the SUS questionnaire), which according to Sauro [294], is above average. However, the author also suggests converting the SUS score to a percentile rank [294]. As such, the results from the participants' answers to the questionnaire are presented in Table 18 and Table 19, allowing the comparison of the achieved SUS scores through three different grading approaches [375], [391].

Table 18 - Number of occurrences of the participants' SUS scores described as percentile ranks and grades.

Percentile range	Grades	Count
96 - 100	A+	12
90 - 95	A	3
80 - 84	B+	3
70 - 79	B	2
41 - 59	C	2
15 - 34	D	4
Lower than the 15th percentile	F	5

Table 19 - Number of occurrences of the participants' SUS scores described using adjectives [375].

Adjectives	Count
Best Imaginable	12
Excellent	3
Good	5
Fair	6
Poor	3
Worst Imaginable	2

Another relevant aspect that should be stressed is the correlation among high SUS scores and high-efficiency values. Users who graded the system with a greater SUS score also achieved higher performance during the hands-on test. The same is true for users scoring lower in the SUS questionnaire as they achieved lower performance. The complete data collected from the summative evaluation is displayed in Appendix III).

From the qualitative assessment, eight emergent subcategories arose throughout the analysis process of the participants' discourses. According to content analysis, subcategories may emerge from the information shared by the interviewees and can be used to complete the categorical tree previously thought by the researchers [387]–[389]. Thus, the updated categorical tree that guided the analysis process consists of three "mother/main" categories and 25 subcategories (Appendix IV).

The categorical planning resulting from Nvivo allowed the organisation and analysis of the information in discourse references attending to the categories and subcategories achieved. In this sense, the presentation of the qualitative analysis of the data is organised into two distinct but complementary stages:

i) the first stage will refer to the direct relationship between categories/subcategories and the number of discursive references associated by the interviewees;

ii) the second stage sought to understand a possible analytical relationship between categories/subcategories: *2. Applicability Pre-test*, and *3. Applicability Post-test*.

Thus, within the scope of the first stage, it is possible to state that:

- Regarding category *1 - Previous knowledge about Virtual Reality*, all interviewees mentioned what kind of knowledge they had about VR.

- Regarding subcategory *1.1. - Contexts where Virtual Reality was first heard*, the most mentioned context is gaming and/or recreation time (subcategory *1.1.1. - Gaming and or Recreation Time*). In detail, 25 participants stated that they first encountered VR in this context, followed by Media (subcategory *1. 1.3. - Media*), with nine answers, followed by Applications within the Construction Industry (*subcategory 1.1.4. - Applications within the Construction Industry*), with six answers, and finally by the Scientific Dissemination context (subcategory *1.1.2. - Scientific Dissemination*) displaying five answers.

- Regarding subcategory *1.2. - Knowledge concerning Virtual Reality applications to facility management*, most interviewees (24) shared having no knowledge concerning VR applications to maintenance (*subcategory 1.2.2. - Interviewees had no knowledge concerning Virtual Reality applications to facility management*), and 7 participants mentioned knowing about VR applied to the maintenance context (*subcategory 1.2.1. - Interviewees had knowledge concerning Virtual Reality applications to facility management*).

- Regarding category *2. Applicability Pre-test*, all interviewees shared their vision concerning the proposed solution's potential as a task facilitator and their perceptions about its impact on their daily professional life.

- Regarding subcategory *2.1. - Virtual Reality as a task facilitator*, 25 participants mentioned that this solution could work as a task facilitator (subcategory *2.1.1. - Virtual Reality applications to facility management as a task facilitator*), and 6 participants indicated that this solution would not work as a task facilitator (subcategory *2.1.2. - Virtual Reality application as a non-facilitator of facility management tasks*).

- Regarding subcategory *2.2. - Impact of Virtual Reality applications,* 24 participants shared the vision of a positive impact of this solution on their professional daily work (subcategory *2.2.1. - Perceived positive impact of Virtual Reality applications to facility management tasks*), 4 participants mentioned having no opinion regarding the possible impact of this solution on their professional daily work (subcategory *2.2.3. - No perceived positive or negative impact of Virtual Reality applications to facility management tasks*), and only two participants shared the vision of a negative impact of this solution on their professional daily work (subcategory *2.2.2. - Perceived negative impact of Virtual Reality applications to facility management tasks*).

- Regarding category *3. - Applicability Post-test,* all interviewees shared their opinion regarding the possibility of implementing this solution in their work context, the usefulness and also the perceived easiness of using the proposed system in their work context.

- Regarding subcategory *3.1. - Perceived possibility of implementation of the proposed Virtual Reality solution*, of the 29 interviewees who answered this question (two interviewees chose not to answer this question), 27 mentioned that this solution is possible to implement in their work environment (subcategory *3.1.1. - It is possible to implement the proposed Virtual Reality solution*), and only two mentioned that this solution is not feasible to implement in their current work context (subcategory *3.1.2. - It is not possible to implement the proposed Virtual Reality solution*).

- Regarding *subcategory 3.2. - Perceived usefulness of the proposed Virtual Reality solution*, of the 26 interviewees who answered this question (5 interviewees chose not to answer this question), 21 responded affirmatively to the usefulness of this solution in their work context (subcategory *3.2.1. - The proposed Virtual Reality solution is useful*), with one interviewee repeating once how much he/she agrees with this sense of usefulness of the solution in question. Conversely, five interviewees responded negatively to the perceived usefulness of the solution if applied to their work environment (subcategory *3.2.2. - The proposed Virtual Reality solution is* *not useful*), with two interviewees repeating once in each of their respective interviews how they do not agree with the sense of usefulness of this solution.

- Regarding subcategory *3.3. - Perceived easiness of use of the proposed Virtual Reality solution*, of the 30 respondents who answered this question, 15 mentioned how easy it was for them to use this solution (subcategory *3.3.1. - The proposed Virtual Reality solution is easy to use*), nine mentioned that this solution would be easy to use after some training (subcategory *3.3.3. - The proposed Virtual Reality solution could be easy to use after some training*), and five mentioned that they did not consider this solution easy to use (subcategory *3.3.2. - The proposed Virtual Reality Solution is not easy to use*).

Regarding the second stage of the analysis aiming to understand the existence of an analytical relationship between categories/subcategories**:** *2. Applicability Pre-test* and *3 Applicability Post-test***,** six interviewees responded negatively to the idea that the proposed VR solution could work as an enabler to the performance of their tasks, giving the following reasons to support their response:

i.) The interviewee considers that there are tasks that must necessarily be done face-to-face;

ii.) The interviewee considers that there are tasks that must necessarily be done face-to-face and that require immediate and more inventive action on the part of the worker;

iii.) The interviewee, as he/she does not know the procedure and real application of this solution to his/her context, argues that he/she cannot perceive VR as a task facilitator;

iv.) The interviewee considers that for the management position he/she now holds in the maintenance sector, this solution does not prove itself useful. However, it may be useful for the teams under his/her supervision working in the field;

v.) The interviewee considers that there are tasks that must unavoidably be done in person and that the entire work process using a digital/computer solution may add unnecessary time to the work he/she already has; and

vi.) The interviewee considers that there are tasks that must necessarily be carried out in person and does not understand how VR could facilitate the performance of these tasks.

Through a deeper comparative analysis between the subcategories 2*.1.2. - Virtual Reality application as a non-facilitator of facility management tasks* and *3.1.1. - It is possible to implement the proposed Virtual Reality solution,* it may be suggested that from the previous six interviewees' answers, four changed their opinion after the hands-on test. Indeed, four interviewees answered affirmatively during the second interview when asked if the proposed solution could be implemented in their work environment.

Likewise, in an equal deeper comparative analysis between subcategory *2.1.2. - Virtual Reality application as a non-facilitator of facility management tasks* and subcategory *3.2.1. - The proposed Virtual Reality solution is useful*, three of the six interviewees changed their opinion responding affirmatively to the sense of usefulness that this application could have in their work context.

Additionally, in an equivalent deeper comparative analysis between subcategory *2.1.2 - Virtual Reality application as a non-facilitator of facility management tasks, 3.3.1 - The proposed Virtual Reality solution is easy to use,* and *3.3.3. - The proposed Virtual Reality solution could be easy to use after some training*, three of the six interviewees stated that they considered this solution easy to use, and two indicated that it could be easy to use after some training.

It should also be noted that of the only two interviewees who responded negatively to the possible positive impact of this solution in their work context, only one changed his mind completely after the test. That is, during the second interview, one interviewee answered affirmatively to all subcategories *3.1.1. - It is possible to implement the proposed Virtual Reality solution, 3.2.1. - The proposed Virtual Reality solution is useful,* and *3.3.3. - The proposed Virtual Reality solution could be easy to use after some training*. The first interviewee who answered negatively about this solution's possible positive impact in their work context only expressed having changed his perception regarding subcategory *3.1.1. - It is possible to implement the proposed Virtual Reality solution, s*tating that it would be possible to apply this solution at his/her workplace.

4.4.4 Discussion

While semantic enrichment of BIM models is more frequently associated with machine learning applications, semantic web technologies, inference rules, or ontology mapping technologies [237], this study focused on an alternative approach to access and improve BIM models' information from end-user input. Indeed, the present research intends to understand the role of BIM-based NUIs and users' empirical and tacit knowledge to increase the LOI of BIM models. In particular, semantic enrichment is applied by increasing BIM models' LOI using gesture and voice interactions within a BIM-based immersive environment.

According to the results, the framework and subsequent prototype allow users with no previous knowledge to interact with BIM models, even those lacking a complete understanding of BIM methodology or experience with BIM authoring tools (83,9% of participants). The fact that most participants completed the test without prior information on how to interact with the immersive VR environment reveals the ease of use of the proposed solution, thus acting as a more natural approach to accessing construction project information.

The acceptance and suitability of the system, based on the results attained, are considered positive. In fact, perceived satisfaction demonstrates a general liking and consent for applying the proposed approach to facility management tasks, even amongst participants with no previous VR or BIM experience.

Another significant aspect that should be stressed is that higher test dropout or inefficiency rates (75%t) were confirmed among participants with educational backgrounds comparable to primary to high school education or a technical or professional degree. Moreover, among the eight participants who did not complete the test, six were 50 years old or older, while five of these participants had lower academic backgrounds. This occurrence could suggest that more training and dissemination about interaction with immersive VR equipment is required among people with such a profile (i.e., users with lower academic backgrounds and/or older ages). Indeed, further research is necessary to ascertain the need to conduct such formative sessions and if additional technical support should be provided for specific groups.

Furthermore, a generalised lack of knowledge about BIM methodology may sustain some participants' reported difficulty in recognising how NUIs and immersive BIM-based environments can be integrated into facility management daily tasks without adding unnecessary time.

Some highlights of the results concerning a possible analytical relationship between categories/subcategories: *2. Applicability Pre-test*, and *3. Applicability Post-test* – second stage of the qualitative analysis – are worth mentioning. In particular, four of six interviewees who had responded negatively during the first interview to the idea that the proposed solution could not facilitate their tasks changed their opinion during the second interview. These participants identified the suggested technological approach as possible to implement in their workplace. Additionally, three of the initial six interviewees identified this solution as useful during the second interview. Also, three of these six interviewees acknowledged the proposed system as easy to use, while two stressed that this solution could be easy to use after some training.

The assessment of new interfaces for the AECO sector through qualitative approaches such as semi-structured interviews provides further information about the suitability of new systems relative to the perceived conditions and working context of the interviewees. This closer relationship with end-users and the data that can be extracted from the verbal and dynamic communication allows for complementing the quantitative analysis carried out in phases such as summative evaluations.

5
CONCLUSION AND DIRECTIONS FOR FUTURE WORKS

5.1 STRUCTURE OF THE CHAPTER

This closing chapter gathers and highlights the contributions of the thesis. The initial section presents an overview of the topics addressed and challenges tackled in the present study, summarising its main contributions to the field of knowledge. The last section consists of indications and recommendations for future research.

5.2 CONCLUSION

Given the advent of Construction 4.0 and attending to the slow full-fledged acceptance of the BIM methodology as opposed to early expectations, this study reflects on the relevance of developing innovative interfaces to allow management of BIM data while assuring that such interfaces are developed according to the requirements, tasks, and contexts of the AECO professionals.

Despite current applications of innovative interfaces, as thoroughly discussed in section 2.5, a gap has been found in a holistic methodology to assure usability evaluations are adapted to the requirements of the AECO sector, which undermines the suitability of the proposed solutions and the comparison between studies. The present thesis is focused on the development of BIM-based immersive interfaces to access and manage project information through an inclusive approach while recommending guidelines for a methodology to assess the suitability of the proposed solutions.

Furthermore, this work emphasises the importance of favouring openBIM solutions, particularly for the use phase, since it extends predictably over decades. In this regard, it is important to avoid the potential technological obsolescence of closed commercial formats and tools with a lifespan significantly shorter than that of the buildings to be managed.

To provide an answer to the central research question of “What techniques would take advantage of the traditional approaches and empirical knowledge of AECO actors in line with the technological advance of the industry?” first, it is necessary to consider the conclusions from the systematic literature reviews.

The literature review on applications of BIM-based VR interfaces identifies benefits that have been verified amongst construction stakeholders, such as improvements in collaboration and communication and providing a means for people with different construction knowledge to access BIM information.

Regarding software preference, most studies report that cross-platform compatibility and an active support community were the main reasons for the selection. Concerning hardware, most authors underpin their selection according to immersiveness, affordability and available functionalities.

Most systems verified a three-layer architecture, including a BIM authoring tool, a visual enhancement tool, and a game engine. Some applications presented a fourth layer related to using a database connection to transfer non-geometric information between the BIM authoring tool and the immersive virtual environment.

BIM-based VR applications were primarily targeted for Design, Pre-construction, Construction, and Operations and Management. The main target groups focused on the screened articles were engineers, architects and workers. Furthermore, owners, facility managers, end-users and students were also mentioned, although with little emphasis.

Limitations are still present with regard to interoperability between software tools. However, recent publications on the bidirectional data exchange of BIM-VR interfaces have been developed, as well as open-source toolkits and commercial software solutions. The latter provide near-instant VR experiences in the form of plugins developed to work within BIM authoring tools (e.g., IrisVR [183], Revizto [184], Fuzor [185], Revit Live [186], Unity Reflect [187]) or as libraries or toolkits to be used by developers (e.g., BIMXplorer [188], IfcOpenShell [189], IFC.js [392]). Additionally, such libraries and toolkits are also prone to be used to develop BIM-based AR interfaces.

Most of the articles analysed do not take advantage of a large part of the dimensions of BIM. Indeed, 3D was the most used BIM dimension, followed by 4D, emphasising the need for more research on frameworks capable of taking advantage of most BIM dimensions.

Regarding the conclusions from the BIM-based AR systematic literature review, it was identified that most applications resort to markerless AR, despite the apparent ease of use of marker-based AR approaches. Indeed and although seemingly easier to apply, marker-based AR systems face limitations as construction sites tend to be complex environments. In particular, markers must be placed carefully and remain visible at all times to provide a well-functioning application. Thus, markerless AR approaches tend to be a more practical alternative [153].

In contrast with VR applications, AR is mostly implemented on construction sites due to the visualisation and information extraction capabilities that it can provide. Favourable examples of construction site applications are found in supporting task completion and reducing construction errors, lowering cognitive workload, improving access to project information, management of construction schedules and costs, enhancing collaboration, increasing site assistance, safety training, task orientation, as well as higher productivity. Moreover, current handheld devices meet the processing power needed to support AR applications, making them suitable for dynamic and cluttered settings such as construction sites.

In terms of hardware preference, mobile devices and touch-based interfaces (i.e., tablets and smartphones) were recognised as the authors' preferred approaches. The potential of gesture-based interfaces and HMDs was also reported (e.g., applications based on Microsoft HoloLens).

Most studies focused on the Construction Management stage, Construction Design, and Collaboration (the latter mostly as a secondary field), while Facility Management, Worker Performance, Education and Construction Safety verified fewer occurrences.

Overall, both technologies (VR and AR) are being progressively employed in the AECO sector despite current limitations and the need for more advantages to be taken by exploring a wider range of BIM dimensions. Results show that BIM-based AR is more prone to be used in construction sites, whereas VR applications are identified in a more diverse range of construction phases.

From the available equipment and timeframe to conduct the present thesis, VR was the selected technology to face the objective of providing innovative approaches to increase the LOI, hence enriching BIM models through task-driven applications, enabling more practical and attuned systems for users with various backgrounds and levels of expertise.

The interfaces were developed according to the DSR methodology for designing artefacts corresponding to practical problems, and the proposed assessment methodology is based on the usability of systems. The usability methodology considers a practical approach to enable future comparisons between similar applications and studies, thus enabling a prompt evaluation of their suitability to the AECO sector. Furthermore, the proposed methodology is a flexible approach to deciding the goals of a usability study, the kind of tests to be conducted (e.g., formative, summative) as well as the choice for convenient usability attributes (e.g., efficiency, effectiveness, satisfaction, learnability, memorability, security, among many others).

The main contribution of the proof of concept, i.e., the preliminary BIM-based interface coupling VR and laser scanning, to the field of knowledge is a workflow to improve the communication between project-related entities. As previously described in section 4.2, the proposed interface enables users to step into an immersive as-is virtual building environment and relay information (as speech) to the design team, thus enriching the associated BIM model. Additionally, preliminary tests confirmed that the interface corresponds to the original objectives of coupling laser scanning and VR within a BIM environment. It should be highlighted that the prototype preliminary tests were merely focused on the runnability of the system, thus providing a stable base to proceed with more complex interfaces in the course of the thesis. In contrast, the development of the second interface is followed by a thorough description of the usability assessment. In detail, the development of the second interface presented in this thesis includes the description of a framework and application of an openBIM-based VR system for the semantic enrichment of BIM models.

A comprehensive description of the system's suitability for the AECO sector is provided, consistent with international usability standards and research recommendations on conducting usability assessments. The usability assessment procedure comprised formative and summative evaluations, as well as the feedback gathered from 62 interviews with 31 AECO professionals.

From the elicited results, eight participants did not complete the test (25,8%), and 74,2% of users completed the test with 100% effectiveness. Most participants scored between B and A+ in the SUS questionnaire, which is consistent with their performance. Additionally, participants were able to interact with BIM information in a natural way using the proposed system, as most participants reached an efficiency level close to that expected from a more experienced user (i.e., high-efficiency values).

From the qualitative assessment, eight *emergent subcategories* arose throughout the analysis process of the participants' discourses resulting in a categorical tree comprising three "mother/main" categories and 25 subcategories (Appendix 1).

This process allowed for an in-depth analysis of individual discourses and the comparative relationship between the categories and subcategories related to the pre-test and post-test interviews. Thus, it should be underlined that the relational proximity with the interviewees, guaranteed through a qualitative methodology [377], made it feasible to reach four key conclusions:

i) Knowledge about VR technology is still commonly associated with recreational and leisure/gaming spaces and moments;

ii) Knowledge of VR solutions applied to maintenance is not very common within this work sector;

iii) Considering the field of maintenance and facility management, most of the interviewees see the proposed solution as having a high positive impact, feasible to implement, and useful and simple to use;

iv) There are still challenges to be overcome, among which:

- A lack of training on the use of this type of solution;

- The fact that most participants are more familiar with the practical, physical and presential type of work than the use of digital tools; and

- AECO professionals resist understanding how this solution could be integrated into their daily work without adding extra time to perform their tasks.

5.3 Directions for future works

Regarding future research, advancements could be made to the presented openBIM framework to streamline the connection to an immersive Digital Twin interface. Such an interface could provide accurate information for planning, managing and training facility management operations.

Concerning the design phase of construction projects, future research may focus on maintenance professionals' recognition of building aspects through the proposed system, consequently streamlining operations in the field. Furthermore, it would be valuable to use a similar approach to enrich BIM models in case inconsistencies are detected on-site that could compromise the execution of maintenance tasks.

The presented openBIM framework is also prone to be used for semantic enrichment through AR applications [393]. Similar system architectures to the one illustrated in section 4.3, Figure 42, could be implemented to convey semantic and geometric information into a game engine handling the interface and interactions designed for AR.

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APPENDIX I

Table 20 - Classification of the screened papers according to computational approach and corresponding BIM Use.

		Papers classification according to BIM Uses								
		Capture Existing Conditions	**Validate Code Compliance**	**Review Design Model**	**Author 4D Model**	**Author Design**	**Analyse Site Selection Criteria**	**Author Construction Site Logistics Model**	**Coordinate Design Model(s)**	**Analyse Energy Performance**
Computational approach	**Deep Learning algorithms (CNN, ANN)**	Stojanovic et al. [242]		Bloch and Sacks [232]						
	Machine Learning algorithms (k-NN, SVM, DT, and NB)		Zhang and El-Gohary [249]							
	Constrained Optimisation	Xue, Lu, and Chen [234] Xue et al. [243]								
	Ontology-based systems	Simeone, Cursi, and Acierno [225] Quattrini, Pierdicca, and Morbidoni [244]	Zhong et al. [248]		Han, Cline, and Golparvar-Fard [257] Karan, Irizarry, and Haymaker [258]	Costa and Madrazo [259]	Karan and Irizarry [239] Karan, Irizarry, and Haymaker [262]	Arslan, Cruz, and Ginhac [263] Arslan, Cruz and Ginhac [264]	Lee et al. [265]	

	Werbrouck et al. [245]								
Semantic Web	Simeone, Cursi, and Acierno [225] Quattrini, Pierdicca, and Morbidoni [244] Werbrouck et al. [245].	Zhong et al. [248]		Karan, Irizarry, and Haymaker [258]	Costa and Madrazo [259]	Karan and Irizarry [239] Karan, Irizarry, and Haymaker [262]		Lee et al. [265]	
Semantic Natural Language techniques		Zhang and El-Gohary [249]							
Forward Chaining			Belsky, Sacks, and Brilakis [223]						
Rule-based Inference	Sacks et al. [233]		Bloch and Sacks [232]						
Visual Programming									Natephra et al. [267]

Other		Mazairac and Beetz [241] Zhiliang et al [238] Dankers, van Geel, Segers [222]	Leet et al. [254]	Hamledari et al. [256]	Koch and Firmenich [261]			Borrmann et al. [266]		

APPENDIX II

CONSENTIMENTO INFORMADO

Gostaríamos de o/a convidar a participar numa sessão de teste de usabilidade no âmbito da tese de doutoramento intitulada ***Development and validation of BIM-based Natural User Interfaces for non-geometrical information management.*** Esta sessão de teste será realizada por Fábio Matoseiro Dinis (aluno de doutoramento) da Faculdade de Engenharia da Universidade do Porto (FEUP), Porto, Portugal. O motivo da sua participação na sessão de testevisa a avaliação da usabilidade de uma interface de Realidade Virtual e prende-se com o seu envolvimento enquanto **profissional responsável pela manutenção.**

A investigação decorrente desta tese de doutoramento dedica-se a produzir conhecimento sobre a aplicação e validação de interfaces de Realidade Virtual baseadas em Building Information Modelling (BIM) assumindo como principal objetivo: propor um *framework*para o enriquecimento semântico de modelos BIM a ser executado por técnicos de gestão e manutenção de edifícios e que seja compatível com o seu ambiente de trabalho e níveis de competência na área do BIM.

Se concordar em participar nesta sessão de teste, integrará dois momentos de avaliação: (1) entrevista; (2) teste da interface. Dará também permissão para a utilização de todos os dados, materiais e inquéritos por questionário produzidos e respondidos no âmbito da referida sessão.

Admite-se que não existem riscos associados a este teste, contudo, como todas as atividades com recursos a ferramentas digitais, o risco de quebra de confidencialidade é impossível de anular. Até ao limite das capacidades do autor da referida tese doutoramento e responsável pela realização deste momento de recolha de dados, as suas respostas neste estudo permanecerão confidenciais. Para minimizar possíveis riscos irão manter-se as gravações fora de "clouds" ou servidores de armazenamento na internet e todos os nomes serão encriptados assim que forem transcritas as entrevistas.

Assinando abaixo indica que:

1. Foi-lhe fornecida informação suficiente sobre a participação nesta sessão de teste. O propósito da sua participação foi explicado de forma clara.

2. A sua participação é completamente voluntária. Não existe coersão explicita ou implícita que condicione a mesma.
3. A participação envolve fazer parte de uma entrevista e teste de uma interface de Realidade Virtual, realizados por um investigador da Universidade do Porto. A sessão terá a duração máxima de 1 hora. Autoriza o investigador a fazer anotações escritas durante a entrevista e permitirá também a gravação de áudio da mesma. No caso de não querer que o áudio da entrevista seja gravado, está totalmente autorizado/a a desistir da participação.
4. Reserva-se o direito de não responder a nenhuma das perguntas. Se se sentir desconfortável de alguma forma durante a sessão, tem o direito a desistir da participação.
5. Recebeu garantias explícitas de que o investigador não o/a identificará pelo nome em nenhum relatório ou produto escrito usando as informações obtidas a partir deta entrevistae que sua confidencialidade como participante deste estudo permanecerá segura.
6. Tem pelo menos 18 anos de idade, leu e entendeu este formulário de consentimento. Teve todas as suas perguntas respondidas e concorda em participar nesta investigação. Poderá ter uma cópia deste formulário.

__________________________ ____

Fábio Matoseiro Dinis (estudante de doutoramento)

Para informações adicionais (se tiver mais questões sobre a investigação e tese de doutoramento ou problemas relacionados com a participação nesta sessão de teste) poderá contactar:

- Fábio Matoseiro Dinis – fabiodinis@fe.up.pt

Obrigado.

APPENDIX III

Table 21 – Data collected from the summative evaluation.

	Previous experience		**Effectiveness**				**Efficiency**								**Satisfaction**			
	BIM	VR	Task 1 (%)	Task 2 (%)	Task 3 (%)	Task 4 (%)	Task 1 (seconds)	Task 1 (%)	Task 2 (seconds)	Task 2 (%)	Task 3 (seconds)	Task 3 (%)	Task 4 (seconds)	Task 4 (%)	SUS score (%)	Percentile range	Adjective	Grade
1	N	N	50	0	0	0	0	0	0	0	0	0	0	0	22,5	Lower than 15%	Worst Imaginable	F
2	N	N	100	100	100	100	815	0	427	70	98	90	73	90	100	96-100	Best Imaginable	A+
3	N	N	0	11,11	28,57	0	0	0	0	0	0	0	0	0	45	Lower than 15%	Worst Imaginable	F
4	N	Y	100	100	100	100	576	20	607	60	124	80	83	90	75	70 – 79	Good	B
5	N	N	100	100	100	100	216	70	937	30	44	100	38	100	82,5	90-95	Excellent	A
6	N	N	66,67	0	0	0	0	0	0	0	0	0	0	0	52,5	15 – 34	Fair	D
7	N	N	100	100	100	100	595	20	235	90	102	90	83	90	87,5	96-100	Best Imaginable	A+
8	N	Y	100	100	100	100	285	60	294	90	297	60	83	90	95	96-100	Best Imaginable	A+
9	N	Y	100	100	100	100	783	0	558	60	73	90	131	80	92,5	96-100	Best Imaginable	A+
10	N	N	100	100	100	100	547	20	464	70	125	80	125	80	85	96-100	Best Imaginable	A+
11	N	N	100	100	100	100	1237	0	429	70	90	90	451	40	57,5	15 – 34	Fair	D
12	N	N	100	100	100	100	1108	0	381	80	161	80	78	90	87,5	96-100	Best Imaginable	A+
13	N	N	100	100	100	100	245	60	228	90	201	70	46	100	67,5	41 – 59	Fair	C
14	N	N	100	100	100	100	153	80	441	70	343	50	116	90	85	96-100	Best Imaginable	A+
15	N	N	0	0	0	0	0	0	0	0	0	0	0	0	55	15 – 34	Fair	D
16	Y	Y	100	100	100	100	347	50	198	90	383	50	118	90	77,5	80-84	Good	B+
17	N	N	100	100	100	100	380	50	391	80	271	60	100	90	62,5	15 – 34	Fair	D
18	N	Y	50	0	0	0	0	0	0	0	0	0	0	0	65	41 – 59	Fair	C
19	N	N	50	0	0	0	0	0	0	0	0	0	0	0	47,5	Lower than 15%	Poor	F
20	N	Y	100	100	100	100	210	70	299	90	183	70	40	100	92,5	96-100	Best Imaginable	A+
21	N	N	66,67	0	0	0	0	0	0	0	0	0	0	0	77,5	80-84	Good	B+
22	N	Y	100	100	100	100	292	60	317	80	152	80	68	90	87,5	96-100	Best Imaginable	A+
23	N	Y	100	100	100	100	473	40	342	80	123	80	55	100	87,5	96-100	Best Imaginable	A+
24	N	N	100	100	100	100	155	80	306	80	62	90	45	100	82,5	90-95	Excellent	A

	Previous experience		Effectiveness				Efficiency								Satisfaction			
	BIM	VR	Task 1 (%)	Task 2 (%)	Task 3 (%)	Task 4 (%)	Task 1 (seconds)	Task 1 (%)	Task 2 (seconds)	Task 2 (%)	Task 3 (seconds)	Task 3 (%)	Task 4 (seconds)	Task 4 (%)	SUS score (%)	Percentile range	Adjective	Grade
25	N	N	100	100	100	100	205	70	1797	0	70	90	88	90	75	70 – 79	Good	B
26	N	N	16,67	0	0	0	0	0	0	0	0	0	0	0	47,5	Lower than 15%	Poor	F
27	N	N	100	100	100	100	156	80	669	50	118	90	519	30	31	Lower than 15%	Poor	F
28	Y	N	100	100	100	100	338	50	447	70	60	90	63	90	77,5	80-84	Good	B+
29	Y	Y	100	100	100	100	136	80	281	90	53	100	50	100	90	96-100	Best Imaginable	A+
30	Y	N	100	100	100	100	173	80	195	90	169	80	88	90	90	96-100	Best Imaginable	A+
31	Y	Y	100	100	100	100	447	40	73	100	44	100	41	100	82,5	90-95	Excellent	A

APPENDIX IV

Table 22 - Updated categorical tree.

Name	Description	Files	References
1 - Previous Knowledge about Virtual Reality	Knowledge that the interviewees had about Virtual Reality before testing the proposed interface.	31	121
1.1. - Contexts Where Virtual Reality was first heard	Reference to the different contexts where interviewees first heard about Virtual Reality.	31	45
1.1.1. - Gaming and or Recreation Time	Subcategory emerged from the interviewees' speeches.	23	25
1.1.2. - Scientific Dissemination	Subcategory emerged from the interviewees' speeches.	5	5
1.1.3. - Media	Subcategory emerged from the interviewees' speeches.	9	9
1.1.4. - Applications within the Construction Industry	Subcategory emerged from the interviewees' speeches.	5	6
1.2. - Knowledge concerning Virtual Reality applications to facility management	Reference to the interviewees' knowledge concerning Virtual Reality applications to facility management.	31	31
1.2.1. - Interviewees had knowledge concerning Virtual Reality applications to facility management	Subcategory emerged from the interviewees' speeches.	7	7

Name	Description	Files	References
1.2.2. - Interviewees had no knowledge concerning Virtual Reality applications to facility management	Subcategory emerged from the interviewees' speeches.	24	24
2 - Applicability Pre-test	Interviewees' perception regarding the applicability and impact of Virtual Reality to facility management tasks prior to testing the proposed interface during the interview.	31	61
2.1. - Virtual Reality as a task facilitator		31	31
2.1.1. - Virtual Reality applications to facility management as a task facilitator		25	25
2.1.2. - Virtual Reality application as a non-facilitator of facility management tasks		6	6
2.2. - Impact of Virtual Reality applications		30	30
2.2.1. - Perceived positive impact of Virtual Reality applications to facility management tasks		24	24
2.2.2. - Perceived negative impact of Virtual Reality applications to facility management tasks		2	2
2.2.3. - No perceived positive or negative impact of Virtual Reality applications to facility management tasks	Subcategory emerged from the interviewees' speeches.	4	4

Name	Description	Files	References
3. - Applicability Pos-test	Interviewees' knowledge and experience regarding the applicability, implementation possibility and ease of use of the proposed BIM-based Virtual Reality interface to facility management tasks, after the hands-on test performed during the interview.	31	88
3.1. - Perceived possibility of implementation of the proposed Virtual Reality solution		29	29
3.1.1. - It is possible to implement the proposed Virtual Reality solution		27	27
3.1.2. - It is not possible to implement the proposed Virtual Reality solution		2	2
3.2. - Perceived usefulness of the proposed Virtual Reality solution		26	29
3.2.1. - The proposed Virtual Reality solution is useful		21	22
3.2.2. - The proposed Virtual Reality solution is not useful		5	7
3.3. - Perceive easiness of use of the proposed Virtual Reality solution		29	30
3.3.1. - The proposed Virtual Reality solution is easy to use		15	15

Name	Description	Files	References
3.3.2. - The proposed Virtual Reality Solution is not easy to use		5	6
3.3.3. - The proposed Virtual Reality solution could be easy to use after some training	Subcategory emerged from the interviewees' speeches.	9	9