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Interconnection of BIM and VR/AR technologies: Possibilities and challenges

MASTER DISSERTATION

Paulo Tomás Caires Teles
MASTER IN INFORMATICS ENGINEERING

UNIVERSIDADE da MADEIRA
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Faculdade de Ciências Exatas e da Engenharia

Master's degree in Computer Engineering

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Abstract

Building information modeling technology (BIM) although it is in the implementation stage, it is present in the architecture, engineering, construction, and operation (AECO) industry for not being considered a simple software, and for its ability to solve problems and barriers and to be considerate. One of the current problems is the flow of information between different softwares and professionals. As such, the Industry Foundation Classes (IFC) standard format solves this issue by being interoperable, reliable, and free of information loss. Virtual Reality technology is evolving in this industry as well, by being present in several fields of the industry, such as design, data exchange, education, training, and collaborative project management. With novel Virtual Reality (VR) technology as well as Building information modeling technology in the industry will be extended in the future. This dissertation examines the reciprocal information flows between these two domains and centres on translating BIM models into VR representations. Through analysis, the dissertation pinpoints possible obstacles and formulates efficacious communication tactics to enable smooth exchanges. During the implementation phase, a Head-Mounted Display (HMD) and Unity3D are used to realize the intended bidirectional communication. Furthermore, the program's relevance to real-world scenarios and versatility is showcased by its application in at least one area within the AECO industry, demonstrating its practical utility. Comprehensive testing is carried out to evaluate the application's usability and efficacy, offering essential insights into its possible influence on the construction industry. With this in mind, this dissertation presents a virtual environment that explores the possibilities of this interconnection with visualization and editing tools created with a game engine. The information exchange between the BIM and the game engine is done through a pipeline, in which the game engine works as a visualizer and editing support tool for the IFC schema.

Keywords— Virtual reality, IFC schema, VR BIM, AECO application

Resumo

A tecnologia de modelagem da informação da construção (BIM), embora esteja em fase de implementação, está presente na indústria de arquitetura, engenharia, construção e operação (AECO) por não ser considerada um software simples, e por sua capacidade de resolver problemas e barreiras e ser atencioso. Um dos problemas atuais é o fluxo de informações entre diferentes softwares e profissionais. Como tal, o formato padrão Industry Foundation Classes (IFC) resolve esse problema por ser interoperável, confiável e livre de perda de informações. A tecnologia de Realidade Virtual também está evoluindo neste setor, ao estar presente em diversas áreas da indústria, como design, troca de dados, educação, treinamento e gerenciamento colaborativo de projetos. Com a nova tecnologia de Realidade Virtual (VR), bem como a tecnologia de modelagem de informações de construção na indústria, serão estendidas no futuro. Esta dissertação examina os fluxos recíprocos de informação entre estes dois domínios e centra-se na tradução de modelos BIM em representações VR. Através da análise, a dissertação identifica possíveis obstáculos e formula táticas de comunicação eficazes para permitir trocas tranquilas. Durante a fase de implementação, um Head-Mounted Display (HMD) e Unity3D são usados para realizar a comunicação bidirecional pretendida. Além disso, a relevância e a versatilidade do programa para cenários do mundo real são demonstradas pela sua aplicação em pelo menos uma área da indústria AECO, demonstrando a sua utilidade prática. Testes abrangentes são realizados para avaliar a usabilidade e eficácia do aplicativo, oferecendo insights essenciais sobre sua possível influência na indústria da construção. Tendo isso em conta, esta dissertação apresenta um ambiente virtual que explora as possibilidades dessa interligação com ferramentas de visualização e edição criadas com um motor de jogo. A troca de informações entre o BIM e o motor de jogo é feita através de um pipeline, no qual o motor de jogo funciona como visualizador e ferramenta de suporte à edição do esquema IFC.

Palavras-Chave—Realidade Virtual, Esquema IFC, RV BIM, Aplicação AECO

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Paulo Teles

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Acronyms list

AECO Architecture, Engineering, Construction and Operation

API Application Programming Interface

BFC BIM Collaboration Format

BIM Building information modeling technology

CSG Constructive Solid Geometry

DAE Collada

HMD Head-mounted display

IDE Integrated development environment

IFC Industry Foundation Classes

ITC-SOPI ITC-Sense of Presence Inventory

PTSD Post-traumatic stress disorder

RFID Radio Frequency Identification

VR Virtual Reality

WSM Wireless Sensor Networks

Chapter 1

Introduction

Building Information Modeling (BIM) is a revolutionary approach to the design, construction, and management of buildings and infrastructure projects. It involves the creation and use of digital representations of physical and functional characteristics of places. BIM technology enables stakeholders to collaborate effectively throughout the entire lifecycle of a project, from conceptualization to operation and maintenance.

Innovation is the cornerstone of advancement in the dynamic field of AECO. BIM and VR, two cutting-edge technologies, have emerged as transformational forces, altering the industry's environment. The combination of BIM and VR technology is a powerful synergy that has the potential to transform the AECO process completely [44].

The fusion of BIM and VR technology is evidence of the sector's persistent dedication to efficiency and innovation. It represents a turning point when immersive visualization and data-driven insight allow stakeholders to surpass conventional constraints. The limitations of traditional two-dimensional representations are transcended by this synergy, allowing architects, engineers, contractors, and clients to explore a world where the lines between the virtual and the real are hazy. The combination of BIM and VR enables experts to examine designs in previously unheard-of detail, move around digital representations of buildings, and assess their appeal, usefulness, and constructability as if they were there. It is a revolutionary union that gives life to intangible notions, enabling informed decision-making and real-time cooperation throughout the project's lifetime.

The Virtual Reality Revolution represents a natural progression in the series of industrial revolutions, potentially redefining human interaction, education, healthcare, and entertainment. The synthesis of technological advancements and scientific insights positions VR as a transformative force in the modern age, ushering in a new era of possibilities that parallel the impact of previous industrial revolutions.

BIM and VR technology provide novel answers to the long-standing issues facing the AECO sector. These technologies have been effectively applied in multiple projects, leading to cost savings, accelerated project timeframes, less mistakes, increased communication, and improved asset management. They are not simply theoretical notions. The industry is on the cusp of a new age marked by increased productivity, sustainability, and overall project success as it continues to adopt these disruptive technologies.

A virtual environment was created in order to interconnect BIM and VR, based on the applied methodologies in the mentioned articles as in the article by Pedro Ferreira et al. [33], and in the proposal of Khalili et al.,2021 [47] since it is one of the few articles that demonstrate an example of how the connection between BIM and VR is made.

The pipeline of this interconnection has as input a common standard file referring to the construction entities, which is divided into three types of files: geometry, information, and materials, after which the output is of the same type as the input, thus making the exchange of information bidirectional.

1.1 Context

This document shows all the work carried out during the two semesters of the 2022/2023 academic year as part of the Dissertation course of the second year of the Master's Degree in Computer Engineering at the Faculty of Exact Sciences and Engineering, an organic unit of the University of Madeira.

Over the years, there has been an immense advance in computer technology, software, the Internet, and the construction sector, which has led to an irreversible change in our society, such as the growing amount and speed of information generated and made available in real and virtual environments, and with the fusion of BIM and VR is not a fleeting trend but a monumental leap forward in the AECO industry.With this in mind, this project aims to assess the (current) potential of linking BIM models with VR models to demonstrate how VR technology can complement BIM models for AECO professionals.

1.2 Problem

Increasingly, in our world, the demand for infrastructure development is growing. With the vast requests for high requirements for civil engineers and architects, companies need help organizing the details and costs of the project. Results in Information Technology offer an excellent opportunity for these companies to solve a significant problem that they have long had as a misunderstanding and lack of efficient correlation between AECO professionals, such as the planning, building, and administration of constructed assets. Cost overruns, project delays, poor design decisions, poor communication, and inefficiencies throughout the construction and operating stages are some of these problems [34].

One of the problems we will address is the Communication and Collaboration Challenges. The AECO sector is, by nature, complicated since it involves many people and disciplines, including architects, engineers, contractors, subcontractors, and clients. The project's success depends on these many stakeholders' ability to communicate and work together effectively. However, conventional communication techniques, such as paper-based drawings and email correspondence, frequently fail to ensure the smooth flow of information. This disjointed strategy may lead to miscommunications, information silos, and stakeholder disputes [107].

BIM (Building Information Modeling) is a digital representation of a building that provides accurate and detailed information about its physical and functional characteristics. It is widely used in the AECO (Architecture, Engineering, Construction, and Operations) industry to improve collaboration, reduce errors, and enhance project outcomes.

A problem of BIM is that the acceptance of the methodology in the construction sector is slow despite the emergence of Construction 4.0, as well as the need for market demand for BIM and the challenges associated with cost and investment as Fábio Matoseiro Dinis reflects in his study [27].

Virtual reality (VR) offers a new dimension to communication and collaboration by providing realistic, engaging settings. Before construction, clients may virtually "walk through" a building to understand the design better and make judgments. VR enables stakeholders to enter the digital depiction of a structure and interact with it at a human size. This skill overcomes linguistic and geographic boundaries and allows stakeholders to more easily understand a design's spatial linkages, aesthetics, and functional components.[45]

VR technology has already been implemented in the AECO industry, as well as in engineering education. With these implementations over the last few years, current limitations and challenges are emerging.

For example, there are still interoperability issues that need to be resolved. The lack of compatibility between BIM software and game engines, by the interoperability limitations between the exported BIM model and the engines for example, Autodesk Revit and Unity, results in the loss of information and time-consuming operations,

1.3 Objectives

The objectives of this work reflect the following:

- Research and demonstration of the conversion of BIM models into VR models and the bidirectional information flows between them. Identification of problems and ways of communication.
- Implementation in Unity3D and an HMD (Oculus Rift).
- Application of VR design in at least one area in the AECO industry.
- Testing the application with construction professionals.

In order to overcome the limitations of the AECO industry, and with the objectives proposed above in mind, a pipeline is proposed that converts BIM models into VR models, in which there is a bidirectional exchange between these worlds, using an HMD in the virtual environment.

A pipeline is needed that allows information, geometry, and materials to be exchanged from the BIM to the virtual environment and vice versa. Since this direction is bidirectional, geometry, information, and even materials must be affected if editing is done on one side, and visible in the other.

1.4 Contributions to the field

Incorporating BIM technology has led to considerable breakthroughs in the building and architecture industries in recent years. BIM makes it easier to create 3D models, which benefits professionals in design, analysis, and project management efficiency. However, there's an increasing demand for tools that facilitate professional collaboration amongst editors and viewers, as well as more engaging and immersive editing and viewing experiences. This work meets this demand by improving BIM model editing and visualization by introducing a unique bidirectional pipeline and an immersive VR Unity application.

1.4.0.1 Bidirectional Pipeline between BIM and VR

The capacity to modify and update models at any point during the project's lifecycle is a critical component of BIM. To facilitate the conversion process and facilitate the import of BIM models into an editable format, we have created a bidirectional pipeline. The Unity game engine and other BIM software platforms can transfer data seamlessly thanks to this pipeline, using only the Industry Foundation Classes (IFC) that is a platform-independent, open data model that enables the exchange of BIM content between different BIM software programs.

1.4.0.2 Immersive VR Unity Application

This immersive Virtual Reality (VR) application using Unity is a consequence of the research done. Head-mounted displays (HMDs) can be used with this program, which provides an interactive 3D environment for viewing, editing, and working together on BIM models. In addition, this program allows the use of the keyboard and mouse if the HMD isn't connected. In addition, users may record their modifications, take notes, modify the elements, and even bring in more models into the original model.

1.4.0.3 Usability Testing

The bidirectional pipeline and VR application were put through usability testing with 15 users from various backgrounds to make sure they were realistic and practical. Among these participants were four seasoned construction engineers who offered insightful feedback on how the program may be used in actual building situations. Our application has been refined based on the usability testing results, making it more effective and user-friendly for experts in the sector.

1.4.0.4 Scientific Article

To spread this demonstration project and add to the academic and professional expertise in the field, a scientific article on building information modelling will be submitted to the PTBIM2024 - 5º Congresso Português de 'Building Information Modelling'. The establishment of this bidirectional pipeline, the VR Unity application, the outcomes of usability testing, and the practical ramifications for the building and architectural sectors will all be covered in summary in this paper.

1.4.0.5 Repository available to the Community

A public repository was made, where the community can freely access the source code and resources of this project. This effort guarantees transparency and accessibility for anyone interested in improving BIM and VR applications in construction and architecture while stimulating further research and adaptation of our technology.

1.5 Structure of dissertation

The dissertation is divided into six chapters.

This chapter presents the background to this dissertation, its context, the problem, the objectives and the contributions on the field.

This is followed by the state of the art as the second chapter, which shows a little of the history of the industrial revolutions up to the improvement of process efficiency and productivity today. This literature review also covers a little about the AECO industry, concerning BIM, IFC, the strengths and weaknesses of the technologies and an explanation of the existing technology tools, applications in this industry, and the development tools that exist, those selected for the development of this project, and a brief conclusion to the chapter.

The third chapter deals with the methodology, divided into, the use cases, the proposed architecture and implementation in last.

The tools used in the development is in the fourth chapter, explaining the the different softwares, with an overview and for what they were chosen.

The evaluation of the system is done by testing the system and evaluating it with various tests to test the usability of the system, all of which are covered in chapter five.

Finally, the sixth chapter presents the conclusion of this work, as well as future work.

Chapter 2

State of art

To obtain recognition of the topic that will be addressed throughout this dissertation, it will be essential to study the current state of knowledge. This section will address how today's society has come to computing and improving efficiency and the importance of linking the AECO sector with BIM, IFC, and its existing technologies, such as Virtual Reality, and its applications that contain enormous untapped potential.

2.1 The Evolution of Industrial Revolutions

The Industrial Revolution has profoundly impacted many facets of civilization. They have changed the nature of the labour market, resulting in modifications to the credentials and abilities needed to obtain jobs [10]. Due to the necessity of preparing people for the shifting demands of the workforce, these revolutions have also impacted education [16]. Furthermore, the production, distribution, and consumption of commodities have all been shaped by the effects of the Industrial Revolution on international trade and economic systems [41].

The late 18th century saw the start of the first industrial revolution, often known as Industrial Revolution 1.0, in Britain (Figure 2.1). The shift from manual labour to mechanized production using steam and water engines was its defining feature [3]. Due to the creation of factories and the mass manufacturing of commodities brought about by this revolution, there was a notable increase in both urbanization and economic growth [9].

The late 19th and early 20th centuries saw the second Industrial Revolution (Figure 2.2), sometimes called Industrial Revolution 2.0. The invention of the assembly line, improvements in electricity, and the application of novel materials like steel were the main forces behind this revolution. According to Kohnová and Salajová [50], these advances enhanced efficiency and larger-scale production of consumer goods.

d

The late 20th century saw the onset of the third industrial revolution (Figure 2.3), sometimes called the Digital Revolution or Industrial Revolution 3.0. Digital technologies, automation, and the ubiquitous use of computers were the hallmarks of this revolution. Increased connectedness and the creation of the Internet resulted from transforming sectors, including manufacturing, finance, and telecommunications [93].

The fourth industrial revolution, often known as Industry 4.0 or IR4.0, is what we are currently going through (Figure 2.4). The incorporation of digital technology, artificial intelligence, and the Internet

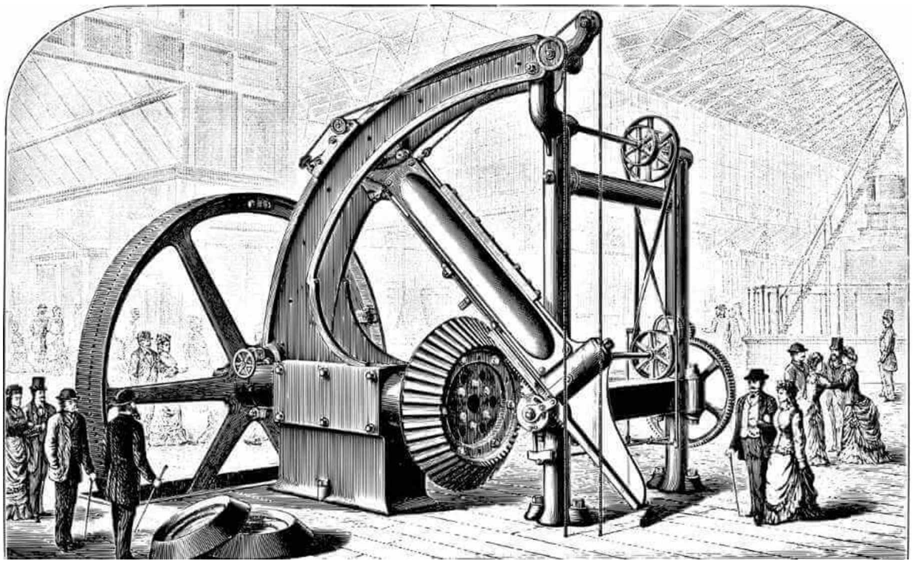

Figure 2.1: Example of an steam machine in the First Industrial Revolution [90]

Figure 2.2: Ilustration of an car from The Second Industrial Revolution [75]

Figure 2.3: Automation with machines in the third industrial revolution [79]

of Things into a variety of businesses is what defines this revolution [98]. It is anticipated to result in substantial modifications to supply chains, business structures, and production procedures [40]. Using cutting-edge technology like robotics, cloud computing, and big data analytics to enhance efficiency and optimize production systems defines Industry 4.0 [40].

Figure 2.4: Head mounted displays as an example of thr fourth Industrial Revolution [66]

Industry 5.0 differs from Industry 4.0 in several key ways. It emphasizes skilled jobs as intellectual professionals collaborate with machines. The main focus of Industry 5.0 is mass customization, with humans guiding robots (Figure 2.5), whereas Industry 4.0 heavily relies on robots for large-scale production. Industry 5.0 aims to enhance customer satisfaction and offers greener solutions, unlike previous industrial transformations that do not prioritize environmental protection. It also utilizes predictive analytics and operating intelligence for more accurate decision-making. In Industry 5.0, a significant portion of the production process is automated, with real-time data collected from machines in collaboration with highly skilled specialists [61].

Figure 2.5: Fifth Industrial Revolution [104]

2.2 AECO industry

The design, construction, and management of structures and infrastructure are all included in the AECO Industry. BIM a crucial idea in the AECO Industry has gained recognition for its ability to transform. Through better collaboration, information sharing, and decision-making throughout the project lifecycle, BIM is a set of tools to increase industry effectiveness and efficiency [87].

As a result of the adoption of BIM, the AECO Industry is moving toward a model-based methodology where data is stored and managed digitally. By facilitating better coordination and communication among project stakeholders, this change can potentially increase industry productivity and lower costs. BIM enables the integration of various technologies, including Wireless Sensor Networks (WSN) and Radio Frequency Identification (RFID), which can further improve the industry's capabilities [59].

Due to the potential advantages it may provide, the AECO Industry is becoming more digital under the umbrella of Industry 5.0 [80]. Aghimien et al. 2021 state that digital technologies, like as BIM, have the potential to increase industrial efficiency, lessen fragmentation, and enable fully integrated and digitalized organizations.

The US AECO Industry has undergone substantial change due to the introduction of advanced construction technologies (ACTs). By facilitating better design, planning, and construction processes, ACTs, including BIM, have increased project quality and efficiency. However, corporations have needed help to create efficient strategies due to the integration of various technologies [69].

Researchers have been interested in learning more about how BIM has developed within the AECO Industry. The amount of development and use of BIM inside a company or Industry is called the maturity of BIM. Smits et al. (2016) state that increased project performance and yield have been linked to higher degrees of BIM maturity [18].

2.3 BIM

BIM (Figure 2.6) is a collection of information known for being a digital database that can create, store, and manipulate large amounts of data generated and maintained during the design, construction, and operations process of a building [76]. This information is represented in a list of properties on each object in the building (on a wall, you can display, for example, its cost, its heat transfer coefficient, and many more properties), which is of great interest to the AECO industry for being a virtual model, which is not only made up of geometry, information, and textures for visualization purposes, but in addition, it is a perfect way to communicate between this industry entities. They can use this model for various mechanical or even electrical purposes, and contractors can use it for planning or preparation. There are several benefits to taking a BIM approach, as it can be applied at various project stages, such as in design, analysis, manufacturing, construction, maintenance and operations, and demolition or renovation. But with so many applications, it is actually used even more in designing and constructing a project [39].

Various disciplines use different software BIM tools from each other, so the sharing and exchanging of information between the software is done by communicating transparently and working with open standards.

Fábio Dinis et al. [27] examined the value of creating cutting-edge interfaces for the administration of Building Information Modeling (BIM) data in the AECO industry. The study emphasizes the necessity for a comprehensive approach to evaluate these interfaces' usability and suggests rules for their creation. Particularly throughout the usage phase of buildings, the need to embrace openBIM solutions and prevent technical obsolescence is underlined.The study also covers the advantages of BIM-based Virtual Reality (VR) interfaces, including enhanced collaboration and communication and the availability of BIM data to various stakeholders.

2.3.1 BIM Modeling vs BIM Model

BIM modeling and BIM models are ideas that are closely connected in the construction and architectural industries, although they have different functions.

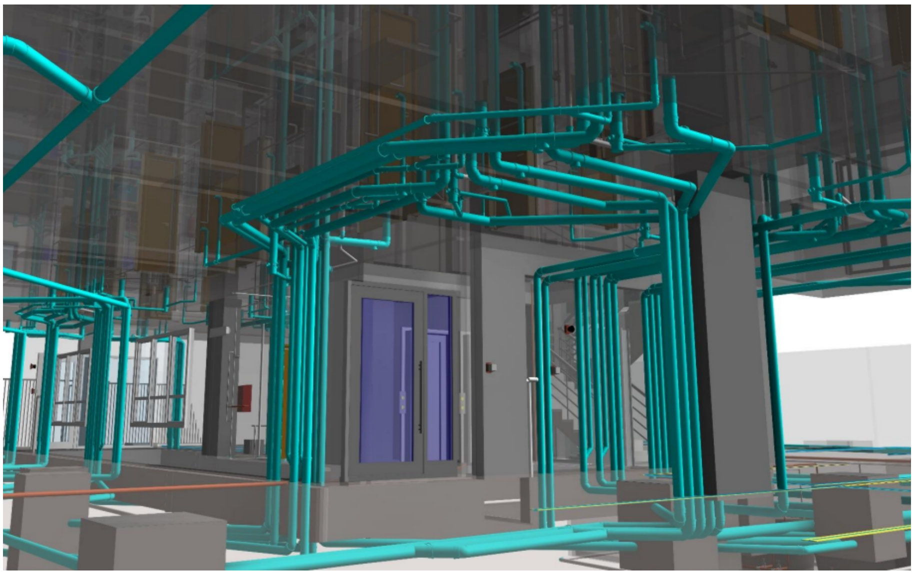

Figure 2.6: BIM example [22]

2.3.1.1 Modeling in BIM

The entire process of developing a digital representation of a building or infrastructure project is referred to as BIM modeling. It comprises using specialist software and tools to create a thorough and sophisticated 3D model that contains not only the structure's actual geometry but also a wealth of information about its parts, materials, systems, and even lifetime statistics. In order to plan, simulate, and manage a construction project more effectively, architects, engineers, contractors, and other stakeholders collaborate through BIM modeling.

2.3.1.2 BIM model

The actual digital output or outcome of BIM modeling, on the other hand, is a BIM model. It is a three-dimensional, information-rich illustration of a structure or facility. Every component of the project is meticulously described in this model, from the walls and windows to the HVAC units and electrical cabling. Throughout a project's lifecycle.

2.3.2 BFC

Before 2010, sharing and asking for changes to a model was a time-consuming procedure that required users to submit the entire model to a different team for comparison. This resulted in a delayed interchange of information. Tekla and Solibri developed an open framework to enable planned information flow amongst applications in response to this problem. By releasing only the most pertinent details and visual representations of the issue, as opposed to the complete file, the intention was to improve cooperation. To improve a prelimiar version of BFC in particular areas, Solibri created a team inside the BuildingSMART Implementer Support Group (ISG) in 2013. This effort finally resulted in the release and adoption of the final BFC version by BuildingSMART at the end of 2014 [68].

BCF is an open XML format file that essentially allows BIM models to access information by dividing the communication from the modeling portion. It has a ZIP format and a folder for each topic or concern the user has brought up. A folder named Globally Unique Identification (GUID), a globally unique label used in software programs as a particular reference of the examined item, is created for each issue the user treats [68].

The BCF format is straightforward to use. The core material generally consists of questions, comments, references, and issues the user has with the BIM model. The users attempting to resolve the matter are subsequently given access to this content [68].

Given the original material, the format also supports additional statuses and comments added by the secondary software. Each issue can additionally have a camera, viewport, or even screenshots of how the case appeared in various auxiliary software linked to it. Currently, the BCF is on version bcfv2.1, which adds the potential for multiple viewports and pictures [68].

An example of an opened BFC in a viewer can be seen in the Figure 2.7 where it is not possible to view the full model, but from the image itself and with the help of the comments, it can be easier to associate.

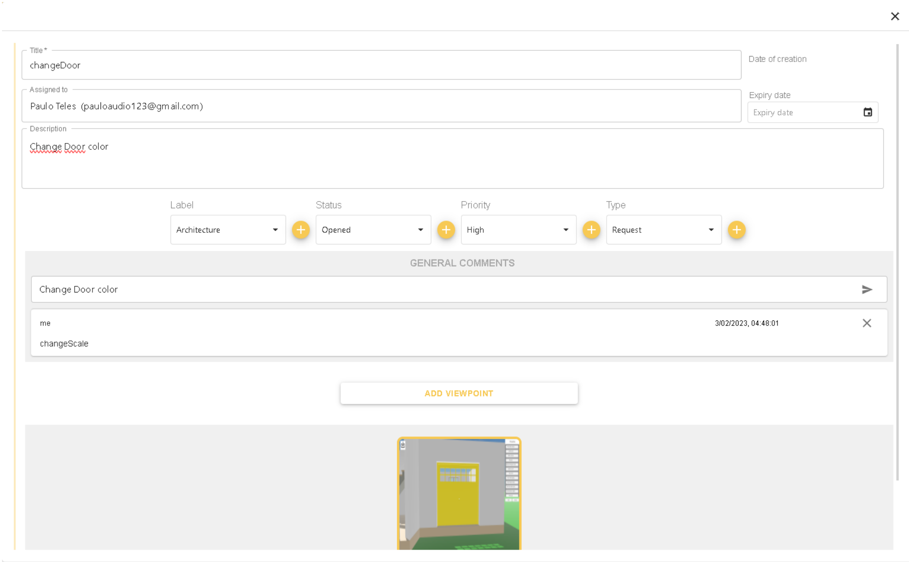

Figure 2.7: BFC example

2.4 IFC

The Industry Foundation Classes (IFC) is an open and neutral file format used in the architecture, engineering, construction, operation and in facilities management industries for the exchange of building information models (BIM) [37]. Developed by the the buildingSMART [20] but who publishes the rules are the International Organization for Standardization (ISO 16739-1:2018) and the International Electrotechnical Commission (IEC), IFC plays a key role in improving Interoperability, communication, and collaboration between stakeholders involved in the life cycle of built assets.

According to Koch et al. (2014), the IFC standard is available in version IFC4 Release and IFC5 version is still in preparation with further parametric capabilities and the activation of the infrastructure domain. It is primarily focused on building construction instead of developing civil infrastructure, including roads, bridges, and tunnels, however, there are ongoing initiatives [49]. An IFC methodology can be seen in the Figure 2.8

2.4.1 Semantic Representation

The IFC employs a comprehensive data schema that defines the semantics of building elements, relationships, properties, and attributes.

This standardized representation ensures that the meaning of the data is preserved in different software applications.

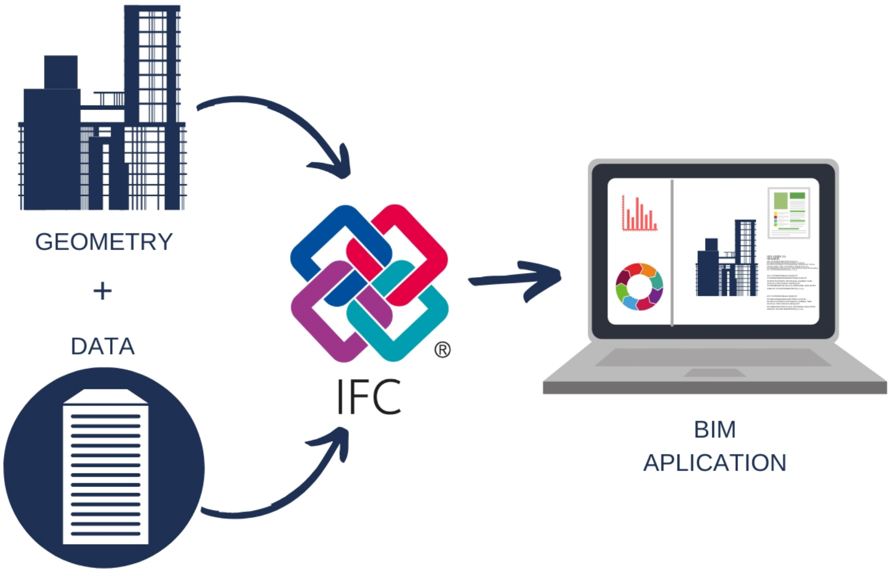

Figure 2.8: IFC squeleton diagram [62]

2.4.2 Open Standard

The IFC is an open standard, meaning it is not the property of any specific software vendor.

This promotes collaboration and avoids dependence on one supplier, allowing stakeholders to choose the software tools that best suit their needs.

2.4.3 Interoperability

IFC enables the seamless exchange of data between various software applications, regardless of their origin or purpose.

This Interoperability is crucial for multidisciplinary collaboration in the AEC/FM industries.

Interoperability in the AECO industry is not yet well defined, and Huahui LAI's article [54] states that traditionally, the information between the different BIM *software* is done point-to-point, as on the left in the Figure 2.10. On the left side we can see the traditional interoperability point-to-point data, where professionals have to exchange data between them, and on the right side the IFC schema is the center and medium of exchange, and reciprocal data sharing between the different BIM programs and professionals.

2.4.4 Full Lifecycle Support

The IFC covers the entire lifecycle of a building, from design and construction to operation and maintenance.

This ensures that information is transmitted accurately at all stages of a building's existence.

2.4.5 Geometric and Non-Geometric Data

IFC supports geometry data (3D models) and non-geometry data (e.g., cost, schedule, thermal properties).

This comprehensive approach facilitates holistic analysis and decision-making.

Figure 2.9: Example of an IFC schema [84]

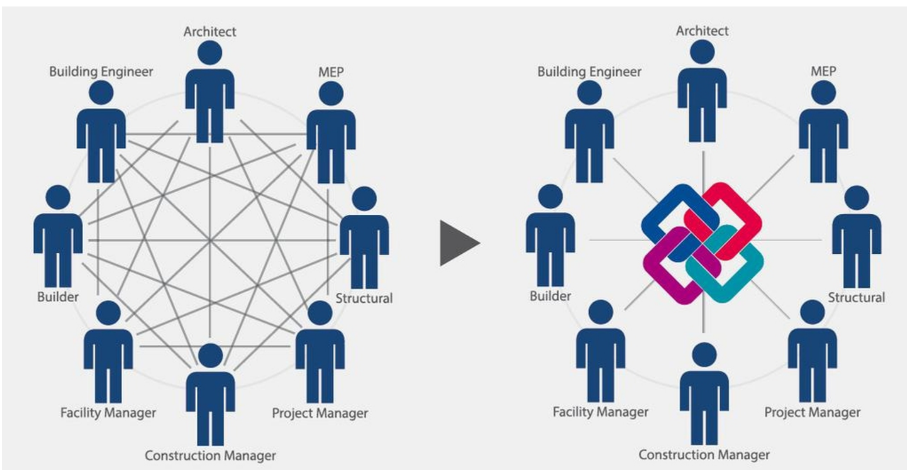

Figure 2.10: Interoperability without and with IFC [11]

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2.4.6 Pros about IFC

Many of the benefits of the IFC are that it is broken down into the following topics:

- Improved Collaboration: IFC fosters collaboration among stakeholders, such as architects, engineers, contractors, and facility managers.

  This leads to better decision-making and reduced errors during the design, construction, and operation stages.

- Reduced Data Loss: IFC's standardized data structure minimizes data loss when transferring models between software applications.

- This ensures that essential information is preserved, avoiding the need for manual re-entry.

- Efficiency and Accuracy: IFC streamlines data exchange processes, reducing the time and effort required for data translation and reconciliation.

  It also minimizes the likelihood of errors caused by misinterpretation.

- Long-Term Data Preservation: IFC's open nature and wide industry adoption contribute to data preservation over the long term.

  As software tools evolve, IFC files can still be interpreted and utilized.

2.4.7 Structure

According to Koch et al. (2014), the IFC framework offers a clear format for information relating to the overall structure of buildings, including definitions of geometry, technical terms, and material relationships. It enables the blending of knowledge about multiple components like concrete, steel, and wool [49]. The IFC schema also permits the semantic fusion of topological conditions, interactions between components of structural systems, and health monitoring system elements [70]. But it is important to keep in mind that the existing IFC model lacks the capability for dynamic assessments [70].

The IFC structure is based on the fundamental ideas determining the meaning of IFC entities, relations, characteristics, and rules [94]. To improve the capabilities of the IFC framework, developments in formal techniques for data collecting, data mining, data analysis, and project planning and control are also required [94].

The IFC schema is composed of three primary components on a very basic level. Figure 2.12 contains a list of them.

- Entities: They resemble the IFC scheme's central nodes. Many entities are grouped in an object-based hierarchy according to the IFC's definition of an entity-relationship model based on EXPRESS. The "Ifc" prefix is used to identify each asset, giving it names like IfcBeam, IfcSpace, and IfcBuilding. A unique identifier for an item in the IFC data model defines it as an IFC entity. Depending on the entity description, the object is given specific default properties and dependencies inside the IFC schema. The Data Dictionary created by BuildingSmart includes a detailed description of each item in IFC. The BuildingSmart Data Dictionary has definitions for each asset. They can be an asset that stores the properties of these elements (IfcRelDefinesByProperties), an entity that governs the relationships between elements (IfcRelAggregates, IfcRelAssigns, etc.), or a building element entity (IfcWall). Figure 2.11 shows a three-dimensional portion of a BIM-created model of a typical building. The names of the respective IFC entities for each component are also displayed on the provided model [89].

- Attributes: It is described as data contained within an entity that is defined by reference to another entity. Direct attributes, inverse attributes, and derived attributes are the three different types of

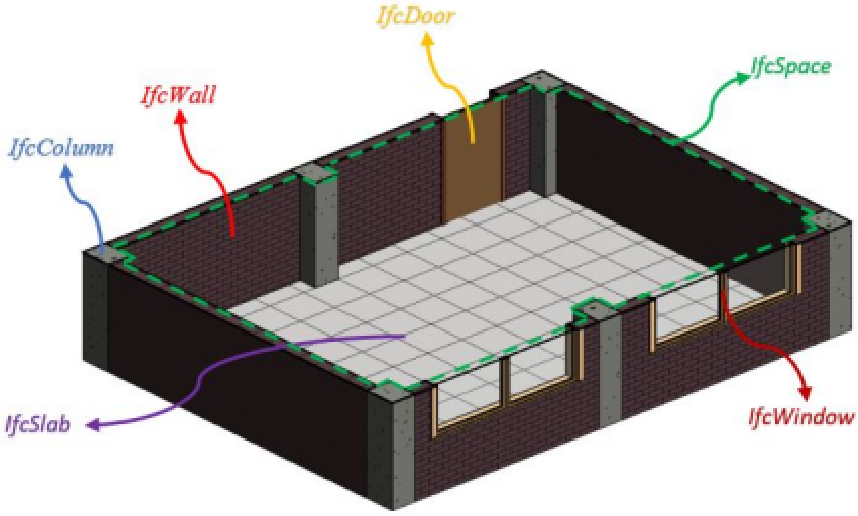

Figure 2.11: Example of IFC entities in a model [89]

attributes. The first four characteristics and definitions that each entity has are as follows, albeit these differ amongst entities [89].

  - GlobalId: Assignment of a globally unique identifier within the entire software world.
  - OwnerHistory: Assignment of the information about the current ownership of that object, including owning actor, application, local identification and information captured about the recent changes of the object.
  - Name: Optional name for use by the participating software systems or users.
  - Description: Optional description, provided for exchanging informative comments.

- Properties: HasPropertySets is an attribute for entities that use elements. This makes it possible to provide the entity a property set—a collection of properties. Individual attributes that further characterize the entity or its performance are included in this set of properties. There are predefined property sets and properties in the schema. Examples include "IfcColumnType" as the entity, "Pset ColumnCommon" as the property set, and "FireRating" as the property [89]. In Figure 2.14 we can see an example where "IFCCOLUMN" is an entidy, "M-CONCRETE-RECTANGULAR-COLUMN:40X50 cm:230358" as the property set of an regular rectangular concrete column with 40x50 cm, and inside that property set, "FireRating" is an property.

The "Project" object, which stands for the complete construction project, is located at the top level of the IFC structure. A group of "Building" objects, which stand in for specific buildings within the project, are listed underneath the Project object. These relationship can be seen in the Figure 2.13.

Many sub-objects represent a particular feature of the building, such as the walls, floors, and roof, within the Building object. Each sub-object has a distinct relationship with its parent object and is arranged in a hierarchical structure.

A Wall object, for instance, may be a child of a Building object and a Door object of a Wall object. This hierarchical framework arranges the architectural and construction data logically and consistently.

The header and the body are the two central portions of the IFC-STEP file. The building model's header section includes general details such as the building model's IFC version, creation date, etc. Examining the header section of the IFC file for the example building model in Figure 2.9 reveals that the IFC file's structure is an IFC 2x3 file. Information about the building model's attributes and shape

Figure 2.12: Basic IFC components [89]

is provided in the body section. Additionally, this part contains details on the relationships that were established between each model component [89].

The hash key cardinal is the first character of each data line in the IFC file's body section. Beginning with number 1, data lines are numbered. Every numbered sequence has an IFC entity. The number of building elements (column, beam, wall, floor, door, window, roof, stairs, etc.) that make up the building model, the preferred material qualities of the elements, and each program operation all affect how many data lines there are in the IFC file. In the BIM program (Revit), each element of the building model and each operation for the model design corresponds to an entity in the IFC data file [89].

The IfcColumn from a column entity example in Figure 2.14, the data line 5771 identifies a building model's column element. Every entity is also comprised of its properties. The properties of each section between the two parentheses after the entity in the data line are defined and separated by commas. In Figure 2.14, each section after the IfcColumn entity in the column element's data line that describes the column element's characteristics is separated from the next by a comma [89].

For instance, the fifth feature in data line 5771 in Figure 2.14 indicates that the column is rectangular with dimensions of 40x50 cm. The IFC entity's locations that start with cardinal point to the entities on the other lines in the file when clicked. In other words, the atribute "41" in the IfcColumn entity's second atribute of the Figure 2.14 refers to line 41 as the location of the information in this attribute. More specific features and details about the column object are contained in the assets on the referred lines. Entities in the referenced lines may likewise refer to assets on other lines. This reference structure continues until a logical data model describes each object precisely [89].

2.4.8 IFC Geometric representations

IFC supports many ways of geometry representation: Constructive solid geometry (CSG), swept geometry (sweep volume, sweeping) as well as Boundary Representation (B-Rep) (Figure 2.15).

A method for representing a 3D shape by defining the limits of its volume. A solid is represented as a collection of connected surface elements, which define the boundary between interior and exterior points.

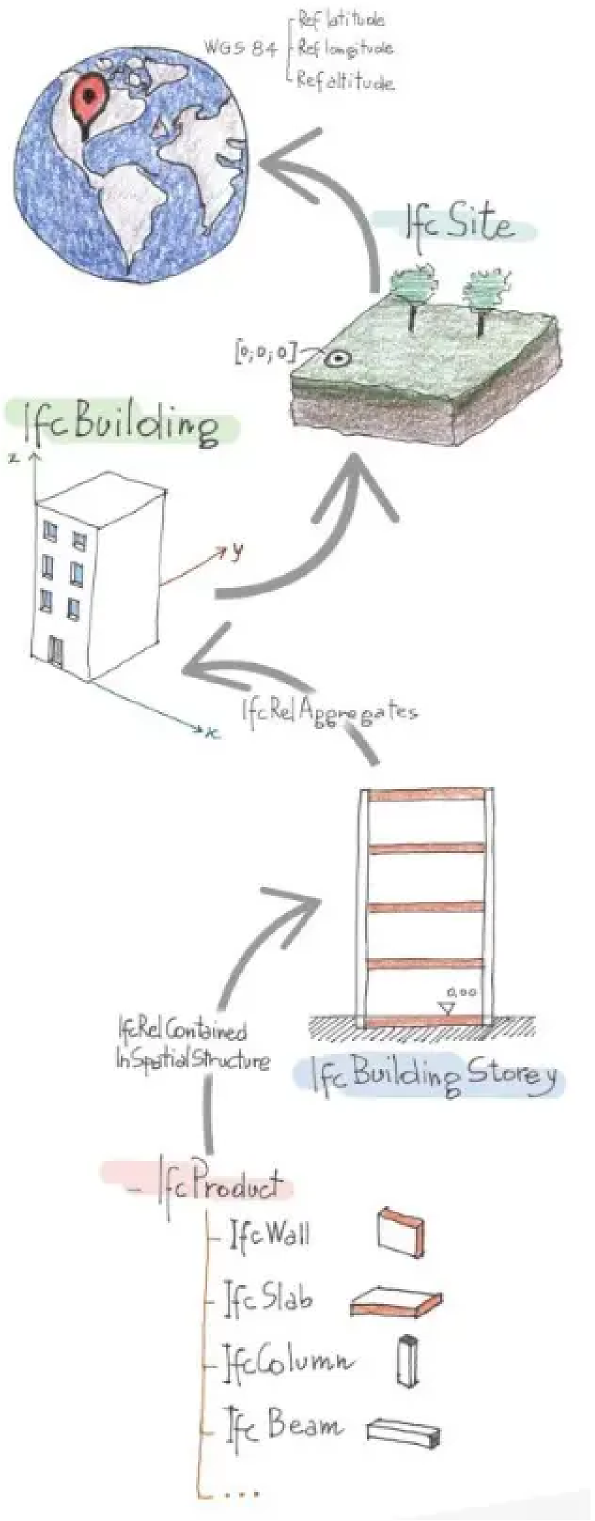

Figure 2.13: Relation between the properties in a IFC [84]

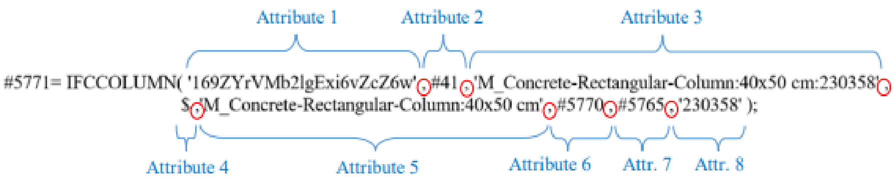

Figure 2.14: Data line of IfcColumn entity in IFC file [89]

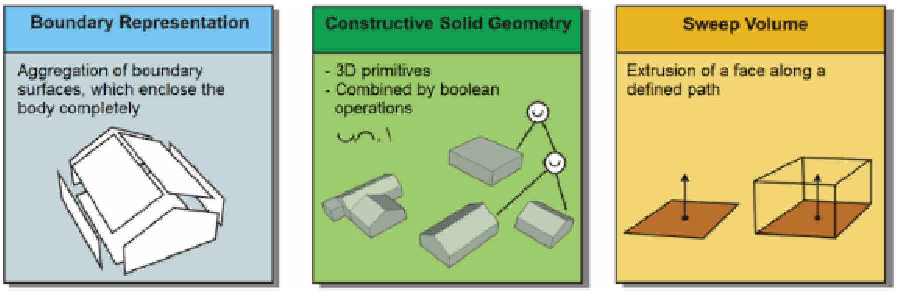

Figure 2.15: The ways of geometry representation in IFC [91]

2.4.8.1 Constructive solid geometry

It essentially consists of using primitive solid objects and doing boolean operations with them, such as fusion, subtraction and intersection, in order to create a final shape.

2.4.8.2 Sweep Volume

The geometric shape of the solid is not dependent upon the curve parameterization; the volume depends upon the area swept and the length of the Directrix.

2.4.8.3 Boundary Representation

In 3D computer graphics, boundary representation, or B-rep, is widely used for representing complicated objects. It combines vertices, edges, and faces to define an object's boundary surfaces. With this representation, things can be rendered with greater accuracy and realism and can be subjected to various operations, including slicing deformation and Boolean operations.

2.4.9 IFC Exportation

According to information published by buildingSMART, all IFC-certified applications can read, write, and share data with other software solutions. IFC, IfcXML, and IfcZIP files can be used to export and exchange IFC files between software applications [62], an example of an exportation can be seen in the Figure 2.16, and all the types can be seen in example in Figure 2.17.

2.4.10 IFC types

Standard (plain IFC)- A basic ASCII text file (only text, no formatting) corresponds to this default interchange format. The scheme specifies how the file's text is converted into objects connected by reciprocal relationships (Figure 2.9) [62].

XML- IFC data files use XML document structures rather than ASCII as they did in the original specification File .ifc. Typically, the .ifcXML (Figure 2.18) file is 300–400 percent bigger than the.ifc file [62].

ZIP- It uses proper compression methods and is a standardized .ifc or .ifcXML compression format. Because .ifc and .ifcXML files are stored as text, this is feasible. Ifc files are typically compressed by 60–80 percent and .ifcXML files by 90–95 percent in .IfcZIP files [62].

2.4.11 STEP

STEP (Standard for the Exchange of Product Model Data)- is a file format that is commonly used to exchange 3D models between different software applications. STEP files can be used to represent a wide range of products, including mechanical parts, electrical components, and architectural designs.

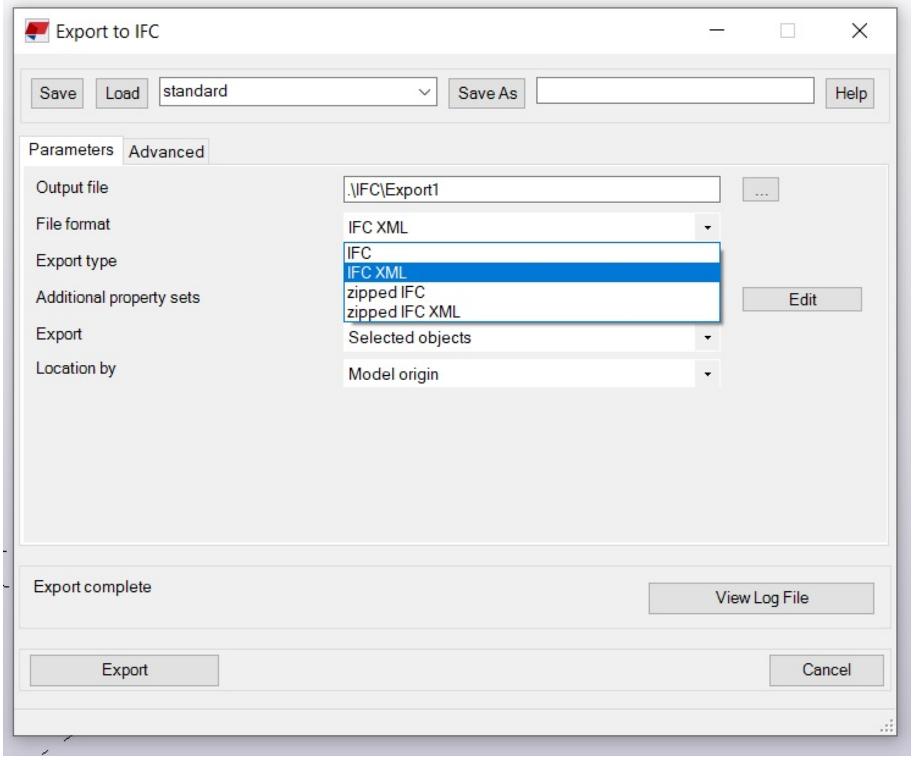

Figure 2.16: IFC exportation [62]

Figure 2.17: IFC types [62]

In the context of IFC files, STEP is used as a means of encoding the data contained within the IFC file. This means that the IFC file can be converted into a STEP file, which can then be read by other software applications that support the STEP format. This helps to ensure that the data contained within the IFC file can be easily shared and used by different stakeholders in the construction industry.

2.4.12 Workflow

Instead of converting IFC files to native objects in various software packages, the optimum approach for applying them includes using them as a reference or executing another scope of work on the project [62].

An architect, for instance, may produce an architectural model using their native tools and export it to IFC. The HVAC designers then receive the IFC model and use it as a guide while running the ducts. The HVAC designers do not modify the IFC model directly in response to changes or issues, such as the need to move a wall or cut a hole in a duct. Instead, they request the changes to the architect, who then makes the necessary changes and exports the revised IFC model [62], an visual example can be seen in the Figure 2.19.

This process ensures that the original IFC model's integrity is upheld and updates are correctly communicated and coordinated among various disciplines. It enables each team to focus on its duties

```
    <TheOrganization>
     <IfcOrganization xsi:nil="true" ref="i2"/>
    </TheOrganization>
   </IfcPersonAndOrganization>
   <IfcApplication id="i4">
    <ApplicationDeveloper>
     <IfcOrganization xsi:nil="true" ref="i2"/>
    </ApplicationDeveloper>
    <Version>2019 Release Candidate</Version>
    <ApplicationFullName>Tekla Structures</ApplicationFullName>
    <ApplicationIdentifier>Multi material modeling</ApplicationIdentifier>
   </IfcApplication>
   <IfcOwnerHistory id="i5">
    <OwningUser>
     <IfcPersonAndOrganization xsi:nil="true" ref="i3"/>
    </OwningUser>
    <OwningApplication>
     <IfcApplication xsi:nil="true" ref="i4"/>
    </OwningApplication>
    <ChangeAction>nochange</ChangeAction>
    <CreationDate>1575233437</CreationDate>
   </IfcOwnerHistory>
   <IfcCartesianPoint id="i6">
    <Coordinates>
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    <DirectionRatios>
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     <ex:double-wrapper>0.</ex:double-wrapper>
     <ex:double-wrapper>0.</ex:double-wrapper>
    </DirectionRatios>
   </IfcDirection>
   <IfcDirection id="i8">
    <DirectionRatios>
     <ex:double-wrapper>0.</ex:double-wrapper>
     <ex:double-wrapper>1.</ex:double-wrapper>
     <ex:double-wrapper>0.</ex:double-wrapper>
    </DirectionRatios>
   </IfcDirection>
   <IfcDirection id="i9">
    <DirectionRatios>
```


Figure 2.18: XML file adopted from [62]

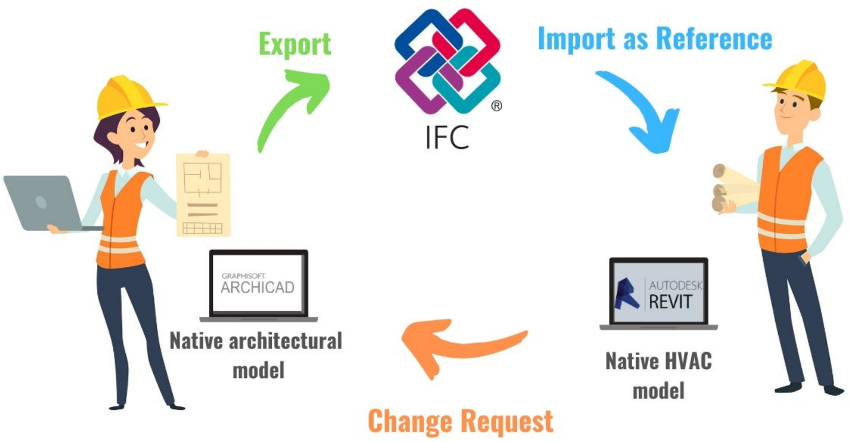


Figure 2.19: IFC workflow [62]

while using the IFC model as a standard reference [62].

2.5 Technologies in the AECO industry

There are many BIM-related technologies available to be applied in the construction Industry, but among them, we can highlight the following technologies:

- Augmented Reality (AR): An overlay of computer-generated content in the real world that can interact superficially with the environment in real time. AR superimposes digital information on the user's real-world environment. Typically, users view AR via a smartphone or a wearable device with a camera (Figure 2.20). A real example would be the AR4C (Figure 2.21), a a mobile field application for site managers to automate their daily work and improve construction performance [73] [55].

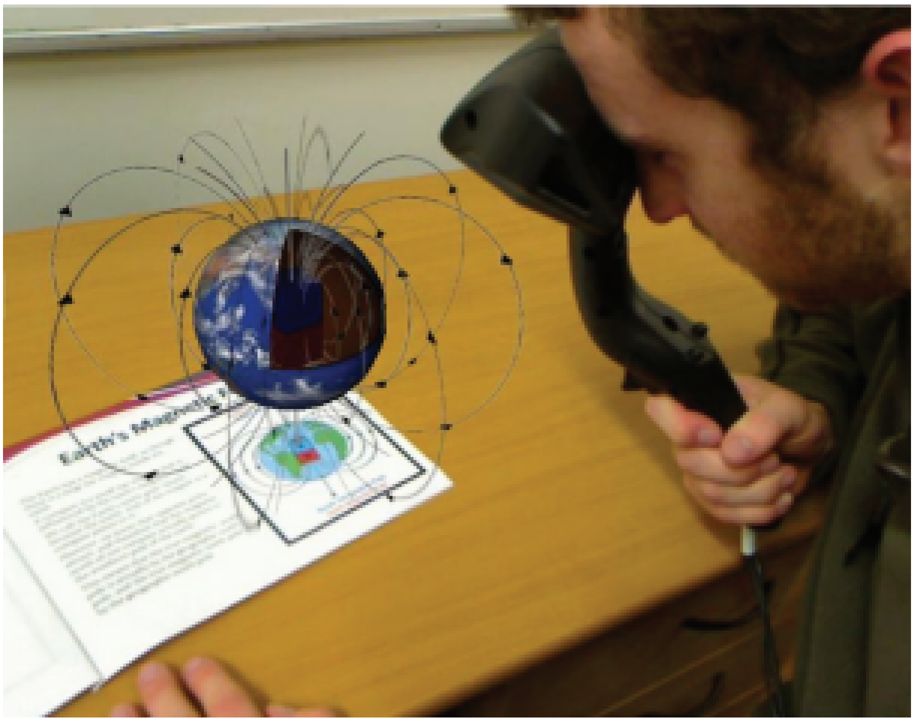


Figure 2.20: Using an interactive augmented book to teach electromagnetism [14]

Figure 2.21: AR4C application used on the construction site [73]

- Virtual reality (VR): Refers to computer technologies that use software to generate realistic images, sounds, and other sensations that represent an immersive environment and simulate the physical presence of a user, VR completely immerses users in a simulated environment, blocking out the real world using a headset that covers their field of vision and often using hand controllers or body tracking for interaction. Usually is used by an Oculus Rift or a HTC Vive [15] [85]
- Mixed Reality (MR): Is another version of AR. Allows users to interact with virtual information

presented in the real world. MR devices follow the user's environment and objects in real-time, examples of which include Magic Leap and Microsoft HoloLens [64].

- Desktop-based uses a simple computer monitor as a platform to accommodate virtual activities via monitors, keyboards, and mice. Users interact with software applications on a screen and are generally used for productivity, content consumption, and communication.

2.5.1 Comparative analysis of the existing technologies

Desktop-based technology is the most commonly adopted and presents a 3D virtual world on a desktop screen without any tracking equipment to support it [96]. However, while the development of desktop technology is relatively stable, VR technology based on BIM, AR, and MR has attracted a lot of attention in recent years.

While the VR experience allows users to be immersed in a digital environment disconnected from the real world, AR allows digital content to be placed "on top" of the natural world. MR allows digital content to interact with the real world, and there are several case studies on each of these technologies in the construction industry.

For the use of MR, this rapidly evolving technology and the software with its challenges, such as the accuracy of spatial registration, the user interface (UI), data storage and transfer, and collaboration, lead the AECO industry not to choose this technology.

The use of AR in real projects presents several significant challenges that must be carefully considered. One of the most apparent issues is localization. Generally, two different approaches are used to find locations within projects, using tools such as GPS and QR codes. Still, both have limitations regarding data transfer or extra work as the project progresses. This technology has several advantages, divided into two categories, in addition to being convenient for the user, such as interactions and decision-making, and user safety. These advantages can be easily realized by VR technology and by solving the problem of AR localization.

Despite existing limits and the need to explore a more extensive range of BIM aspects, both VR and AR are being increasingly used in the AECO industry. While VR applications are seen in various building phases, BIM-based AR is often deployed on construction sites.

2.6 VR in the AECO industry

VR technology is used in the AECO industry in several applications thanks to its ability to make it possible to simulate, test, and open doors that, in reality, are more difficult or impossible to reach. Besides the fact that a VR model, for example, saves on project costs by removing the need to use mock-ups, it presents a detailed representation of the working environment and the machinery, equipment, and machines that may be present. In addition, it allows the client to be involved in the design process, allowing them to make prior decisions or investigate any problems that would not be possible to observe in the two-dimensional plans. VR technologies offer new opportunities to effectively train and educate new students, or those with higher education, without the existence of the real risk [56]. These students can have immersive experiences from medical students, engineering, mechanics, and student to pilots [101]. Sepehr [8], conducted a case study that allowed scientists, engineers, and others from other disciplines to walk on Mars. His objective was to test, compare, and choose the different scenarios, construction, materials, and building processes, as in an adventure in the NASA and Mars environment, everyone could experience scenarios, validate decisions, and review mistakes. This helps the team understand all the details, priorities, future work, and conclusions. With this study, it was possible to conclude that

VR with BIM shows great potential, such as providing interactive renderings, spatial coordination, and virtual models that can be used for several uses.

Another study by Emma Buchanan investigates the use of Virtual Reality VR in Architectural Design Reviews, concentrating on whether or not seeing Building Information Modeling (BIM) information through VR improves the review procedure. Healthcare experts who assessed the design of a hospital using either PDF architectural blueprints and a 3D digital desktop model or a VR model were involved in user research to determine this. According to the study, those who used virtual reality VR performed activities more quickly and at a greater rate. The majority of participants chose VR as their review condition of choice. These results lead the study to the conclusion that VR may be used to see BIM information and improve the efficiency of design reviews [19].

2.7 Applications of VR in the AECO industry

There are several applications of VR, and for the sake of organization when mentioning these applications, the division of these applications into categories can be done by the guidance of some articles [77] [83] [99]. Therefore we can group the applications in terms of:

- Design and data exchange.
- Collaborative project management.
- Education and training.

2.7.1 Design and data exchange

The areas of architecture engineering and design have seen a considerable transformation thanks to virtual reality (VR), which provides innovative tools and approaches for those working in these professions.

Through the use of virtual reality (VR), architects and designers may produce 3D models of their projects that are immersive and incredibly realistic. A more excellent grasp of spatial connections, size, and architectural purpose is made possible by these immersive walkthroughs. Architects engineers and designers recreate real-world settings using virtual reality (VR). This include researching aspects like ambient lighting, acoustics, and material performance under various circumstances to help with design decisions. By enabling customers to visually "walk through" their future rooms, this improves client involvement and pleasure while also clarifying design principles.

VR is helpful in the preservation and restoration of old structures and locations. Using virtual reality, architects may accurately scan and recreate historical sites in 3D detail, assisting in their conservation and repair. VR technologies simulate sustainability and energy efficiency variables to assist architects in assessing the environmental effect of their ideas. This enables building designs to be optimized for lower energy use. Cruz-Neira's study [25] describes the design and technical setup of the CAVE and emphasizes its creative application of surround-screen projection technologies. The CAVE system has significantly advanced the area of virtual reality technology by having an impact on the creation of interactive simulations and virtual reality settings.

An example of this application, is the study by Jing et al. [32] who introduced a real-time BIM-VR data synchronization system, by updating BIM changes, in the VR environment (Figure 2.22 and 2.23).

Stefan et al. [100], conducted two case studies, the first, was a visualization experiment of a VR model, which demonstrated that there is a need for improved information flow in the AECO industry, and that VR technology would be of great help. The other case focused on the opinion of the client about VR models by the client.

Figure 2.22: Three users using BVRS to coordinate design changes [32]

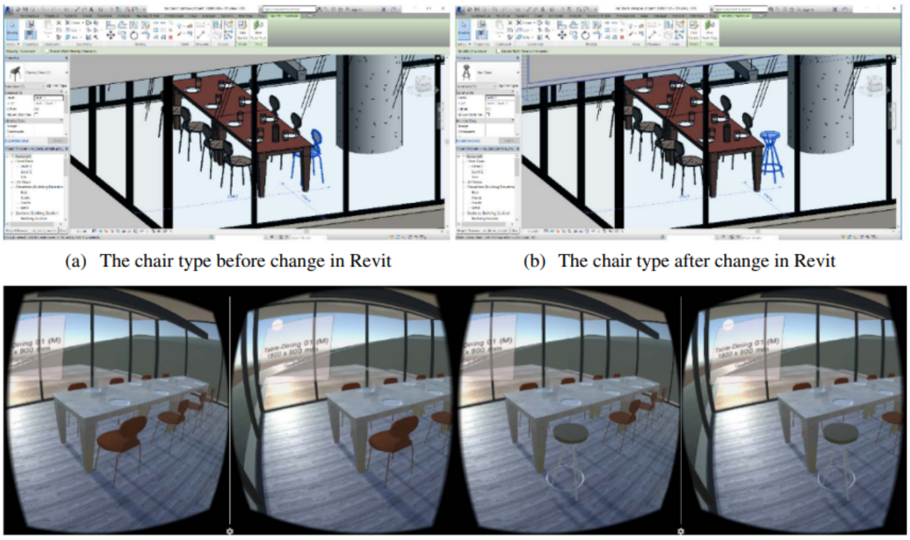


Figure 2.23: Changing object type in Revit and changes updated in VR [32]

Also by using VR, we can display projects in 3D, architects and urban planners enable stakeholders to interact with virtual representations of structures and spaces.

Numerous real-world instances demonstrate how BIM and VR technology may be successfully integrated. For example, using BIM and VR considerably improved the construction of the Louvre Abu Dhabi. While stakeholders could explore the museum's galleries before construction started, architects and engineers used BIM models to coordinate and visualize the complex architectural features [71].

This scientific investigation of Pottinger explain the application of virtual building methods to construct the Louvre Abu Dhabi Museum (Figure 2.24). The study focuses on using virtual reality (VR) and building information modeling (BIM) technology in the building process. It explores the difficulties encountered during the building process, including complicated geometry, elaborate structural systems, and some requirements. It highlights the advantages of utilizing virtual building methods to meet these issues. Finally, it offers insightful information about successfully applying virtual building methods in a challenging architecture project. The study underlines the significance of BIM, VR, and AR technologies in attaining effective project results and demonstrates how they have the potential to revolutionize the construction Industry.

Similar to this, the Shanghai Tower, one of the tallest structures in the world, was built with the use of BIM and VR. The project team could spot conflicts and address design concerns thanks to integrating BIM models and VR walkthroughs, which made the construction process more effective.The project's design architect and the owner recognized from the start that BIM and an integrated design approach were necessary to handle the complexity of the design, collaborate effectively, and produce better sustainable

Figure 2.24: Louvre Abu Dhabi's [21]

Figure 2.25: Social Influence on Construction Safety Behaviors: A Multi-User Virtual Reality Experiment [82]

results. Additionally, the everyday operation of the tower, equipment management, real estate management, and emergency management are all scheduled to use BIM data. BIM optimized the material used, using 14 percent less glass than a square building of the same area, and assisted the project design team in choosing the best tower design that reduces the wind load by 24 percent (each 5 percent reduction equates to roughly USD 12 million). It also demonstrates the revolutionary effects of BIM technology on project management, sustainability, and the building process, along with its integration with VR and AR [72].

Another example of high-profile project, would be the Istanbul airport that was designed using BIM and VR, enabling the construction team to identify issues early in the design process and reduce construction costs [52].

2.7.2 Education and training

To gain new knowledge, students or beginners are tasked with series of subjects, with a blackboard, sheets and presentations given by an experienced professional, with this, information overload and lack of visual elements is present [36](as cited in Xiao et al.,2018 [56]). VR creates powerful, immersive learning experiences that engage students in deeper learning by providing learning through a "situated learning" approach. In a situated learning context, students develop knowledge and understanding through concrete, hands-on experiences built on realistic problems, this approach is beneficial for students with physical disabilities.

The immersive quality of VR improves learning opportunities. It has been demonstrated that medical training in virtual environments enhances decision-making and procedural abilities, as the research from

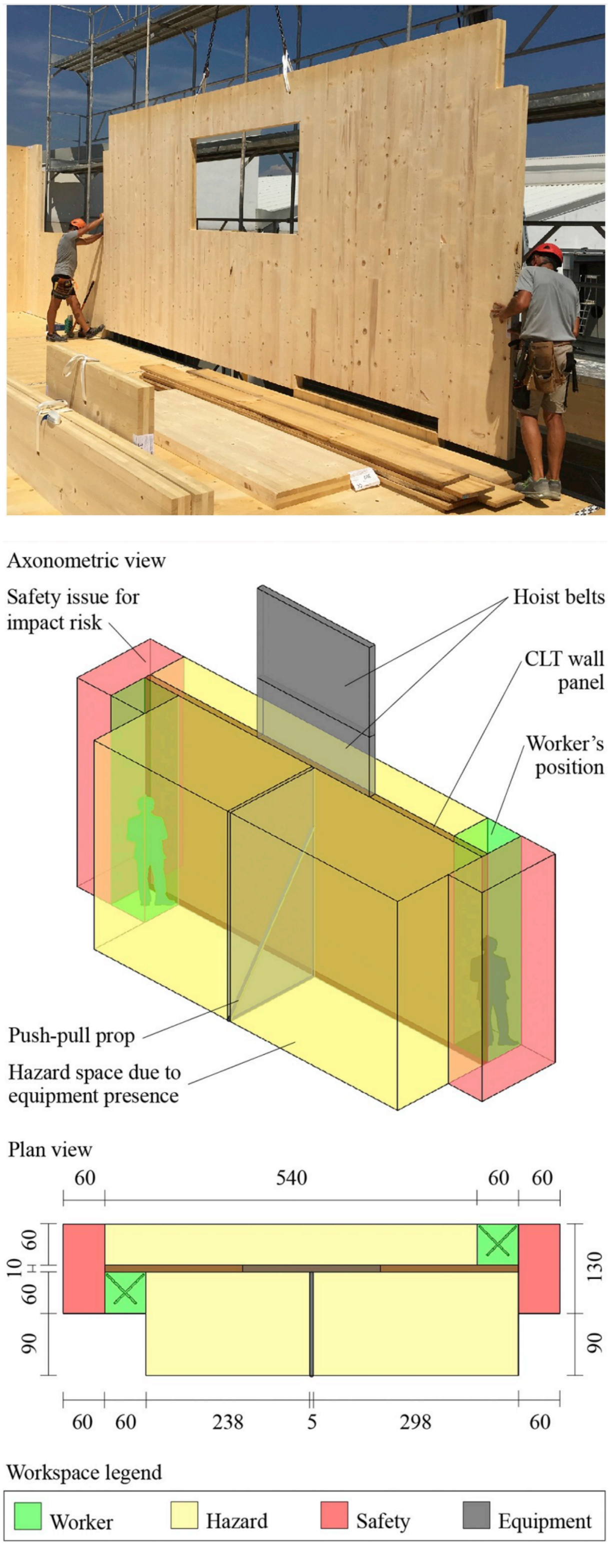


Figure 2.26: BIM model of the workspace configuration for the installation activity of a Cross-Laminated [38].

Seymour et al. in 2002 [81], that examined how virtual reality (VR) training affected people's operating room performance. This randomized, double-blinded study found that operating room performance significantly improved after VR training. The study's conclusions imply that immersive VR training can improve surgical abilities and potentially have real-world medical training and teaching applications.

VR promotes collaborative learning by allowing teachers/students based in different geographic locations to collaboratively design, review and analyze, test and validate projects virtually [101]. There are other potentials of VR in education by being able to reduce language barriers in international learning, by providing the chance to feedback by the instructor immediately, as well as offering the possibility to repeat out of danger exercises in order to practice [7]. In help to that, their training can be more efficient on the job site, this can be expensive, intense, time consuming and potentially dangerous depending on actual site situations such as:

- Schedule conflicts.
- Difficulties of access.
- Weather situations.
- Safety and responsibility needs as shown in Figure 2.25 and 2.26.

Therefore, with the evolution of VR-related technologies from visualization-based training to field experience-based training, it increases the awareness as the practice of students for in [56] safety.

According to Xiao et al. [56], virtual reality training, was initially designed to rehearse the construction process, as well as apply or learn the risks, and safety applications in a danger free virtual environment, so the information was easily learned and easily applied by workers.

Fábio Dinis et al. [29] additionally conducted in this category, a study in which VR interfaces were developed and tested, showing that VR is valuable for Engineering education, concluding that students even with differences in their age and academic group, with no or little training, can easily, learn virtual interaction, gain knowledge, and understand new concepts (Figure 2.27).

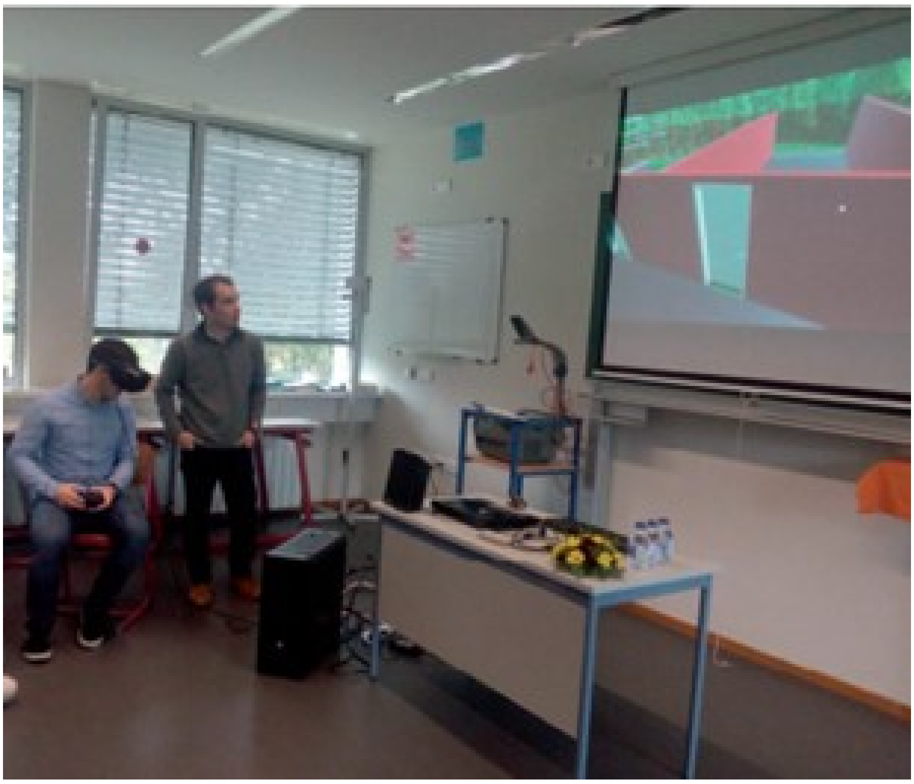


Figure 2.27: VR workshop at a local school: Using colour codes to identify building systems [29]

Other articles by Fábio Dinis [30] [28], demonstrate the ability to activate or deactivate the visibility (Figure 2.28) of a group of elements, allowed access to systems such as plumbing elements, which are usually hidden, or with difficult access. This showed that with virtual access, the need to visit the site for example, of the plumbing itself was prevented, or if this is not possible, the opportunity to see it was created, which proves that VR can overcome many of the existing real barriers.

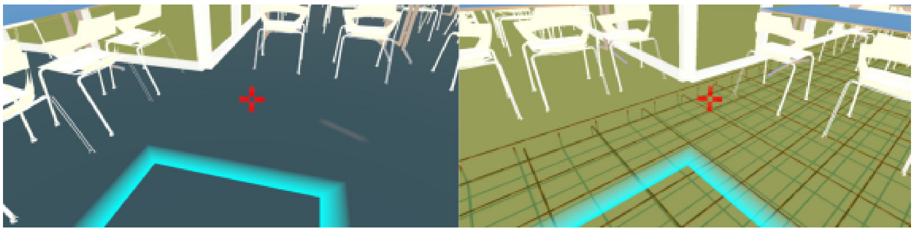


Figure 2.28: Visualization of the rebars hidden within the concrete slab from Fábio Dinis work [30]

Sepehr et al. [7] led a summary of the worldwide advances regarding BIM and VR in the AECO industry, as well as building a model to show best practices in integrating a BIM model with VR technologies, and in evaluating the performance of different BIM-VR environments in terms of their impact on students in aspects of performance in learning, training, and education.

Sepehr et al. [6], reviews previous work on VR in the AECO industry, in design and in education, as well as evaluating the use of VR through a Master of Project Management (MPM) program at Northwestern University, where he concluded that the benefits of VR in education would be, the increased use of creativity, the ability to visualize a complex project design in the virtual environment, and the ability to easily understand important course concepts.

VR can also be used as, simulation and preparation for a crisis situation, as Alper et al. [46] mentions, in which VR served as a training tool that helps residents prepare in fire and earthquake situations in the context of a target building and its surroundings. The VR application developed in order to prove the above statement, this simulates what to do, what not to do, and visualizing the dangerous elements, as well as the safe ones.

2.7.3 Collaborative project management

Even at great distances, VR makes collaborative design sessions possible. In virtual settings, architects engineers and designers may collaborate on projects while promoting creativity and effective communication.

Schnabel [78] makes a substantial contribution to the design and collaborative use of virtual environments. This research paper shows the idea and creation of the first virtual environment design studio. The work is remarkable because it represents an essential first step in the result of design processes and techniques within virtual environments, showcasing the trailblazing efforts in this developing subject, even though particular details are not provided.

As an example of this application with VR in another context, Y.-C. Lin et al. [57](as cited in [33]), in order to improve communication problems between the medical team, stakeholders, and design teams, he created a VR and BIM based communication simulation system, he concluded that his system, improved communication efficiency, but also facilitated visual interactions, and the decision making process. Again Fábio Dinis et al. [31] collaborated on an article in which he refers to an auxiliary tool for designing a briefing in order to transmit to the stakeholders the requirements, and the information needed for them. With the help of VR and a laser scanning within a BIM environment, it was possible to obtain a mesh as an asset in Unity with the proper textures, through laser scanning. No usability evaluations were done, but this tool can be very well used for other project states, as well for other purposes, in the area of civil engineering (Figures 2.29, 2.30, 2.31 and 2.32).

Ali et al. [2] work, in investigating the strengths and weaknesses of VR-based communications compared to face-to-face for construction projects. By conducting an evaluation with their VR communication simulation experiment, they concluded that VR can be an alternative communication channel between remotely located organizations while providing valuable information. We can see an example from the

Figure 2.29: Laser scanning (point cloud) [31]

Figure 2.30: Importing the mesh as an as set into Unity: mesh with out colour information (left); coloured meshes with their respective textures (right) [31]

Figure 2.31: Placing an annotation within the VR interface [31].

Figures 2.36 and 2.37. Alper et al. [46], can be an application in this context because its system, can be used as a training of a crisis simulation.

In the Operation and Maintenance in BIM, checking the accessibility of building components, and facility management, are present in the studies of Abiola et al. [5] (Figures 2.33, 2.34, 2.35 and Chih et al. [102] (Figure 2.38), respectively.

In the workspace planning category, Vito et al. [38], in his study revealed that VR can be used to improve the configuration of workspaces in a construction, but in addition improve the safety procedures

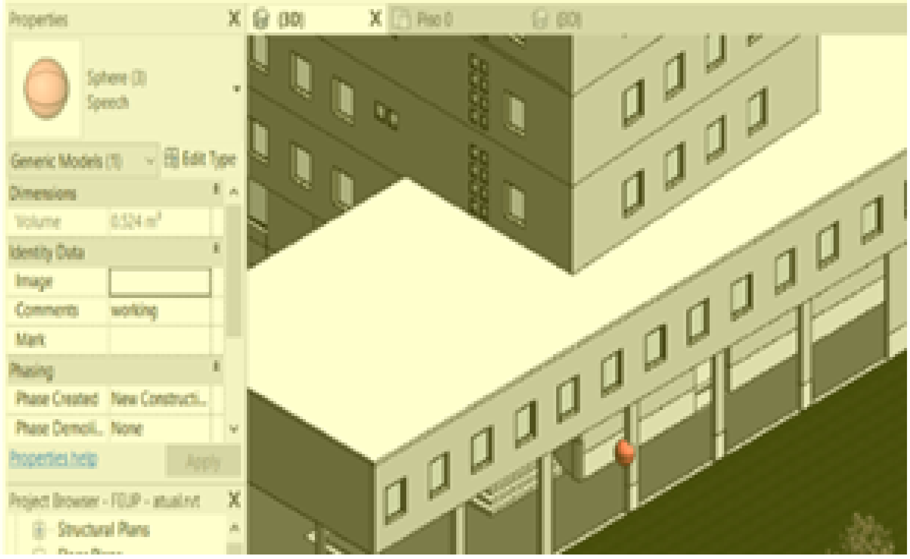


Figure 2.32: Information sphere 3D representation [31].

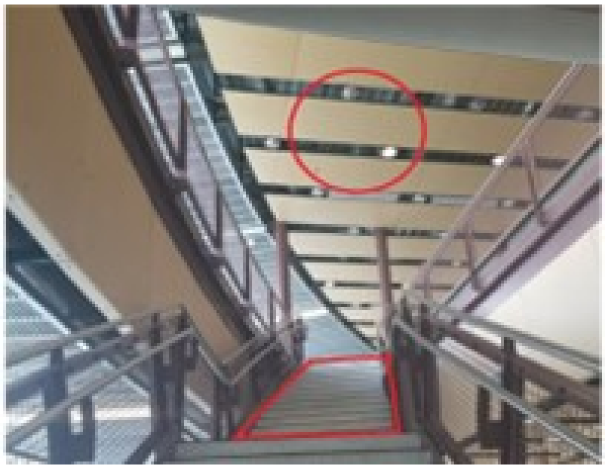


Figure 2.33: Automated checking of building component accessibility for maintenance in VR [5]-Inaccessible light fixture above stairs.

defined in the health and safety plan of a project, by creating a VR-based planning project for the installation of cross-laminated wood panels (Figure 2.26).

2.8 IFC schema implementation in VR

The IFC schema, is also present in VR applications, as in Khalili et al.,2021 [47]'s proposal, an XML-based approach in the exchange of information from BIM to VR applications, by creating an interpolation in which is transposed not only the geometry of each element of the model, but in addition, the information of the model. In another context, Wyke et al. [103] developed a system for acoustic room design, due to the fact that often in the design stages, are overlooked, in the context of acoustic assessment. So the tool proposed by SS Wyke simulates these designs in order to allow non-specialist to hear the room, using existing 3D models in IFC schema. Another example already mentioned here, is the application of Alper et al. [46] in crisis simulation (Figure 2.39), by creating a framework, which allows internal processes in spatial planning, by presenting a shell ontology, on the integration of BIM (IFC schema) and GIS (CityGML), to perform queries of the elements in the model. In addition the study by Aguacil Moreno et al. [4], engaged in the accomplishment of a data management in VR, by combining an IFC schema-BIM model and a building based on the Internet Of Things in terms of management systems. This project

Figure 2.34: Automated checking of building component accessibility for maintenance in VR [5]-
Inaccessible air conditioning system.

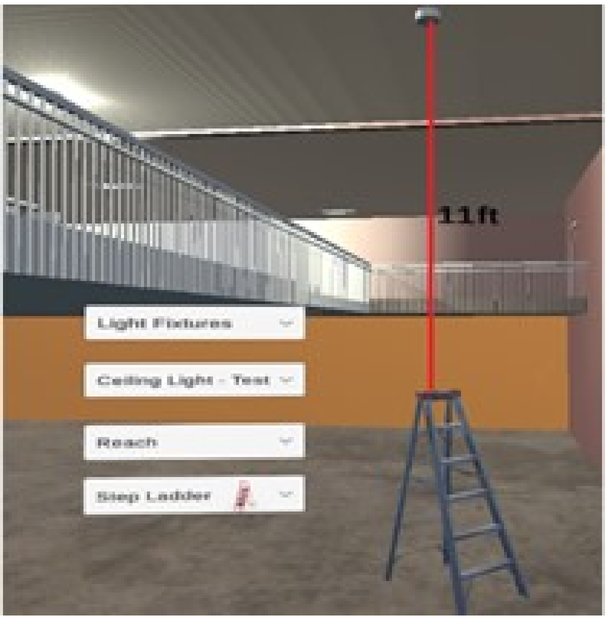


Figure 2.35: Automated checking of building component accessibility for maintenance in VR [5]-
Measurement of fixture height with a virtual laser.

allows to interact with sensor data and manipulate real actuators in the virtual environment. With these and many more applications of IFC schema in VR, they show that its integration is possible.

2.9 Existing tools

For this project, to create a virtual environment that involves Building Information Modeling (BIM), an analysis of existing tools is a need. The more well known are the ones that are gonna be discussed. These tools can be divided into two sectors: hardware and software. In the software, there can be different tools that cover BIM, and on the other side, for the game engine, and in terms of hardware, the different

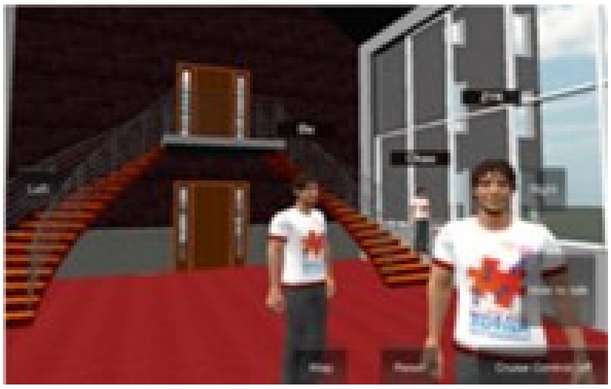


Figure 2.36: Example of Virtual Communication in the IVR Envrionment with Avatars [2]

Figure 2.37: IVR-Based Communication [2]

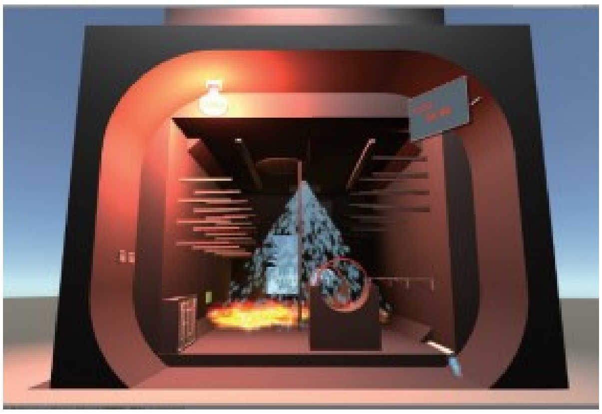


Figure 2.38: Alarm system trigger scenario [102]

physical tools possible to experience virtual reality.

2.9.1 Software

2.9.1.1 BIM Software

Regarding BIM software, we have Autodesk Revit, Graphisoft ArchiCAD, and Trimble SketchUp, each of which will be detailed below:

- Autodesk Revit: A Building information modeling (BIM) software created by Autodesk, Inc. It has developed into a crucial tool for planning, capturing, and controlling building projects in the architectural, engineering, and construction (AEC) Industry. Revit provides a full range of tools for architects, structural engineers, MEP (mechanical, electrical, and plumbing) engineers, and

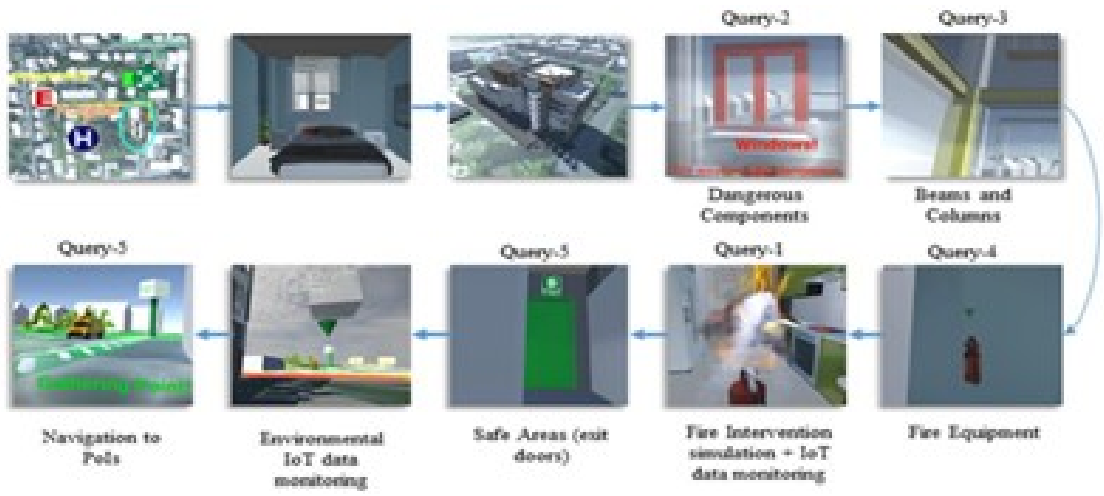


Figure 2.39: VR-enabled disaster training simulator [46]

construction specialists for the collaborative creation and management of building designs.

- Graphisoft ArchiCAD: Another popular BIM program with 3D modeling features is ArchiCAD. It enables architectural visualization by enabling the creation of BIM-compatible models for VR integration as mentioned by Kim [48], that explains that in order to enhance waste management and sustainability in building projects, this research creates an estimating framework that makes use of Building Information Modeling (BIM) to anticipate the composition of demolition trash and classify it by kind.

- Trimble SketchUp: A 3D modeling program is utilized for various tasks, such as engineering, interior design, and architecture. It is renowned for its user-friendly tools and interface, which make it simple for users to build, modify, and view 3D models. BIM-compatible models may be produced using SketchUp's user-friendly 3D modeling environment, and these models can subsequently be included in VR applications.

2.9.1.2 VR Development Platforms

In VR Development Platforms, the more popualr are the Unity3D and the Unreal Engine, these platforms can be defined as:

- Unity3D: A well-liked and adaptable game creation environment that enables the production of 2D, 3D, augmented reality (AR), and virtual reality (VR) games and apps. Its user-friendly interface, and has an extensive library of resources. A flexible game development engine, that has an intuitive user interface and is frequently used to build VR apps that display BIM data.

- Unreal Engine: Created by Epic Games the robust and popular gaming engine. It is employed not just in the creation of video games but also in the simulation, virtual reality, and film industries to provide immersive real-time 3D experiences. Unreal Engine is a well-liked option for developers and designers to bring their interactive and virtual worlds to life since it provides superior graphical capabilities, a strong collection of tools, and a visual scripting system. It is suitable for creating visually stunning VR experiences with BIM models, as it offers advanced graphics feature.

2.9.2 Hardware

As far as hardware is concerned, we can find VR headsets and motion controllers, a simple definition of each of which is given below:

- VR Headsets: This wearable gadget is fully immerse people in 3D settings created by computers. A pair of goggles or glasses with integrated displays, sensors, and frequently audio components make up most of them. When worn, VR headsets follow the wearer's head movements and alter the show appropriately, generating a realistic and immersive virtual experience that may be used for various tasks, including gaming, simulations, education, and other uses. These gadget can be the Oculus Rift and HTC Vive, are crucial pieces of gear for using VR apps. They increase the realism of BIM-based VR experiences by providing rich 3D images and tracking capabilities.

- Motion Controllers: These are a portable input devices intended for use with virtual reality. They frequently go hand-in-hand with VR headsets, allowing users to engage with virtual worlds by monitoring their hand and gesture motions. Users may grasp, move, and interact with items in the virtual environment with these controllers, which frequently have buttons, triggers, and sensors that imitate real-world motions. The sensation of immersion and engagement in VR applications, such as games and simulations, is improved with VR motion controllers.

2.9.3 Full existing tools

As mencioned by Fábio Dinis et al. [27], there are already near-instantaneous VR experiences in the form of plug-ins developed to work with BIM creation tools that profoundly influenced the AECO Industry, such as IrisVR, Revizto, Fuzor, RevitLive, and Unity Reflect, by improving visualization, collaboration, and coordination procedures.

These technologies are primarily used in commercial software applications, and are present in many case studies, reviews, and industry reports that demonstrate their practical uses and advantages in the AECO Industry. This tools can be:

- IrisVR: Architects, engineers, and construction industry experts may envision and experience their ideas at a human size using the virtual reality (VR) software platform IrisVR. Users of IrisVR may get fully immersed in their virtual worlds, exploring their projects and making knowledgeable judgments regarding design revisions. The program works with various file formats, including Revit, SketchUp, and Rhino, so that it may be used with well-known design programs. Perkins+Will and Turner Construction, among others, have employed IrisVR to improve stakeholder cooperation and communication [95].

- Revizto: Building information models (BIM) may be reviewed, tracked, and managed by teams in an intuitive setting using Revizto, a collaborative software solution. Revizto allows project members to annotate models, assign tasks, and write issue reports to speed up the cooperation process. Additionally, the platform provides real-time synchronization, enabling team members to access the most recent data. Major AEC companies like HOK and AECOM have used Revizto to enhance project coordination and lower mistakes during the design and construction stages [74].

- Fuzor: A BIM and VR software program called Fuzor combines the capability of project coordination and visualization. It enables users to build immersive virtual reality experiences by importing their BIM models. Fuzor's collision detection, scheduling, and cost-estimating tools help project teams find issues early on in the design process and find solutions. Companies like Skanska and BuroHappold have started using the software to increase design quality, collaborate more effectively, and speed up construction operations [35].

- RevitLive: Architects and designers may turn their Revit models into interactive 3D experiences using the Autodesk software product called RevitLive. Users using RevitLive may explore their ideas in real time, move about areas, and make judgments about designs as they go. A virtual reality headset may be used with the program for an even more realistic experience. Firms like

Gensler and SOM have used RevitLive to display designs to clients, streamline design reviews, and increase stakeholder participation. Unfortunately this tool is no longer available [58].

- Unity Reflect: A real-time 3D software program called Unity Reflect links BIM models with other stakeholders' and architects' designs. It enables users to collaborate with and see their designs in a group setting. Revit is one of the many file types that Unity Reflect supports, making it simple to integrate with current design workflows. Companies like Woods Bagot and Zaha Hadid Architects have embraced the program to better decision-making, increase visualization, and speed up project execution [88].

2.9.4 Libraries or toolkits

These following toolkits collectively illustrate the advancements in BIM technology and the efforts to improve collaboration, interoperability, and visualization within the AECO industry: BIMXplorer, IfcOpenShell, IfcConverter, IFC.js, XBIM. They aim to enhance the understanding, analysis, and decision-making processes by enabling users to access, manipulate, and visualize BIM data effectively. This toolkits can be for example:

- BIMXplorer: A BIMXplorer toolset focuses on giving people access to building information models (BIM) so they may study and traverse them. Users can better grasp the BIM data thanks to its interactive display and analysis features. BIMXplorer facilitates enhanced decision-making during the design and construction process by allowing stakeholders to interact with the BIM model. It places the value of greater collaboration and immersive experiences in the perspective of BIM [17].
- IfcOpenShell: Industry Foundation Classes (IFC) files may be processed and manipulated using the free, open-source software toolkit, IfcOpenShell. IFC is a standardized file format for BIM data sharing and exchange across various software programs. For working with IFC data, IfcOpenShell offers several tools, such as parsing, converting, and model analysis. It places the demand for data sharing and interoperability within the AECO Industry in context [43].
- IfcConverter: IFCConverter is a powerful tool that allows the conversion of IFC files into other formats, such as CSV, XML, and JSON, among others. It is part of the IFCOpenShell suite of open-source tools that enable the use of Industry Foundation Classes (IFC) data . IFCConverter is a command-line tool that can be used on various operating systems, including Windows, macOS, and Linux. The tool provides a range of options for customizing the output format, such as selecting specific IFC entities, filtering properties, and defining output formats.
- IFC.js: The issue of access to BIM application development, brought on by the high cost of adopting IFC solutions, is addressed by the open-source project IFC.js. You can load, examine, and modify IFC models in browsers, desktop programs, and mobile applications thanks to this multi-language library (C++, TypeScript, and JavaScript) [84].
- XBIM: BIM models may be created, managed, and visualized with the help of the open-source toolset known as XBIM (eXtensible Building Information Modelling). It offers model validation, geometry processing, and visualization features for using IFC data. In several BIM-related research investigations and initiatives, including conflict detection, energy performance analysis, and model-based collaboration, XBIM has been used. It places the value of BIM tools in how they serve various facets of the building process, from quality assurance to performance analysis [60].

2.9.5 3D formats for Unity

There are various 3D formats compatible with Unity, which can be obtained from BIM software. Below are the different types of files that can be used for the 3D representation of a BIM model in Unity. There's multiple formats for Unity for example:

- DXF: Drawing exchange format, or DXF, is a type of CAD (computer-aided design) file format. It was developed by Autodesk and is utilized for data interchange across several CAD software packages. Vector images found in DXF files may be resized without sacrificing quality. DXF (Drawing Exchange File) is a representation of all data labeled information found in the ASCII or binary AutoCAD file format as well as the graphics file. It may be used as a graphic file exchange and input/output interface between AutoCAD and other graphics programs.A DXF file is made up of six segments, or SECTIONs, in total. These segments included the file ending character (group code is 0, group value is EOF), HEADER, CLASSES, TABLES, BLOCKS, and ENTITIES [105]. The DXF file structure and each segment's significance are displayed in Appendix A.

- OBJ: A file format used for 3D models is called OBJ (Object). Widely employed in the computer graphics industry, it was created by Wavefront Technologies. 3D geometry, texture coordinates, and material data may all be stored in OBJ files.This outdated format has been supported by ARCHICAD for a very long time. This is a very dependable format with broad visualization support. An example of this format can be seen in the Figure 2.40. As shown in the figure, the letter "v" depicts a vertex of an element in terms of x,y, and z coordinates. The letter "f" corresponds to the faces of the component. For example: f 1 2 3, represents that the face contains the first, second, and third vertex. In addition it can also have texture mapping.

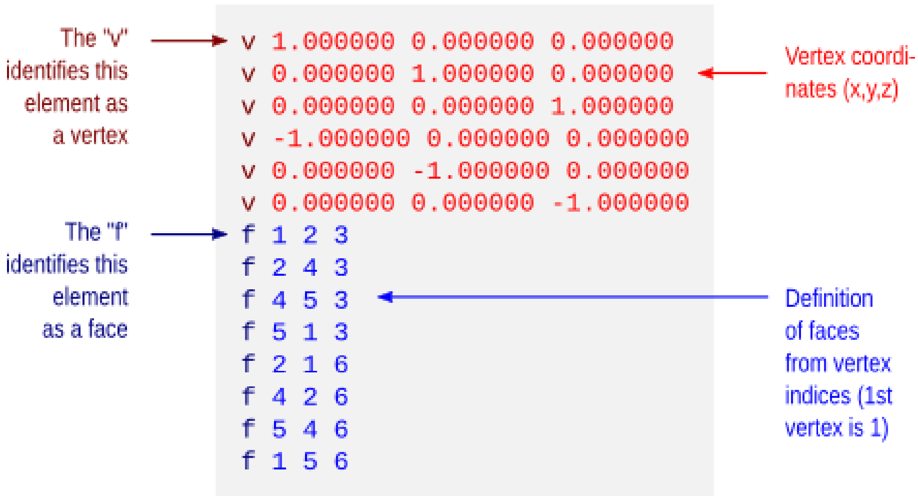


Figure 2.40: OBJ example

- MTL: A file format called MTL (Material Template Library) is used to store material data for 3D models. It works in tandem with OBJ files and has the ability to contain data like color, transparency, and texture mapping. An example of an MTL file is shown below:

```
newmtl shinyred
Ka  0.1986  0.0000  0.0000
Kd  0.5922  0.0166  0.0000
Ks  0.5974  0.2084  0.2084
illum 2
Ns 100.2237
```

  In the example above, the MTL file structure is defined by:

  - Ka r g b

    Defines the ambient color of the material to be (r,g,b). The default is (0.2,0.2,0.2);

– Kd r g b

Defines the diffuse color of the material to be (r,g,b). The default is (0.8,0.8,0.8);

– Ks r g b

Defines the specular color of the material to be (r,g,b). This color shows up in highlights. The default is (1.0,1.0,1.0);

– d alpha

Defines the non-transparency of the material to be alpha. The default is 1.0 (not transparent at all). The quantities d and Tr are the opposites of each other, and specifying transparency or nontransparency is simply a matter of user convenience.

– Tr alpha

Defines the transparency of the material to be alpha. The default is 0.0 (not transparent at all). The quantities d and Tr are the opposites of each other, and specifying transparency or nontransparency is simply a matter of user convenience.

– Ns s

Defines the shininess of the material to be s. The default is 0.0;

– illum n

Denotes the illumination model used by the material. illum = 1 indicates a flat material with no specular highlights, so the value of Ks is not used. illum = 2 denotes the presence of specular highlights, and so a specification for Ks is required.

– map Ka filename

Names a file containing a texture map, which should just be an ASCII dump of RGB values.

- 3DS: A file format for 3D models can be seen in the Figure 2.41. It was created by Autodesk and is mostly utilized in the entertainment and gaming sectors. 3D geometry, texture coordinates, and material data may all be stored in 3DS files. It represents 3D Sudio (DOS) mesh file format used by Autodesk 3D Studio, it is one of the most widely used file formats for 3D data import and export provides information for 3D representation of sceneries and pictures. Construct vertices and polygons for rendering a scene. It considers camera positions, mesh data, lighting data, viewport configurations, smoothing group data, bitmap references, and characteristics.
- DAE: For 3D models, there is a file format called DAE (Collada). It was created by the Khronos Group with the intention of serving as an open standard for the transfer of 3D data across various software programs. 3D geometry, texture coordinates, material details, and animation data may all be stored in DAE files. An example of the structure of trhis file format can be seen in the Figure 2.42, as well as an example of the look of a DAE file in photoshop in the Figure 2.43.
- FBX: The file format for 3D models is called FBX (Filmbox). It was created by Autodesk and is extensively utilized in the entertainment and gaming sectors. 3D geometry, texture coordinates, material details, camera details, and animation data may all be stored in FBX files [53].

2.10 Conclusion

The thorough examination of the current state of the art in the fusion of virtual reality (VR) and building information modeling (BIM) technologies has given this thesis's methodology significant context

Figure 2.41: 3DS File [1]

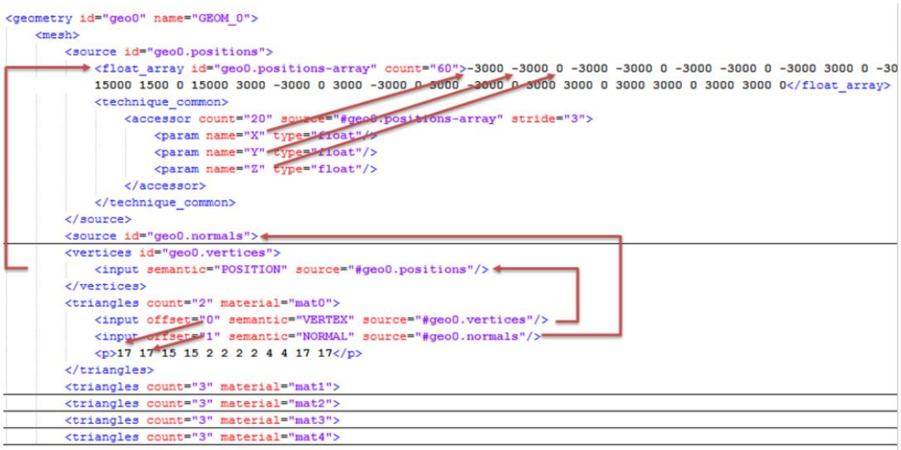


Figure 2.42: Collada (*.dae) file structure adopted from [24]

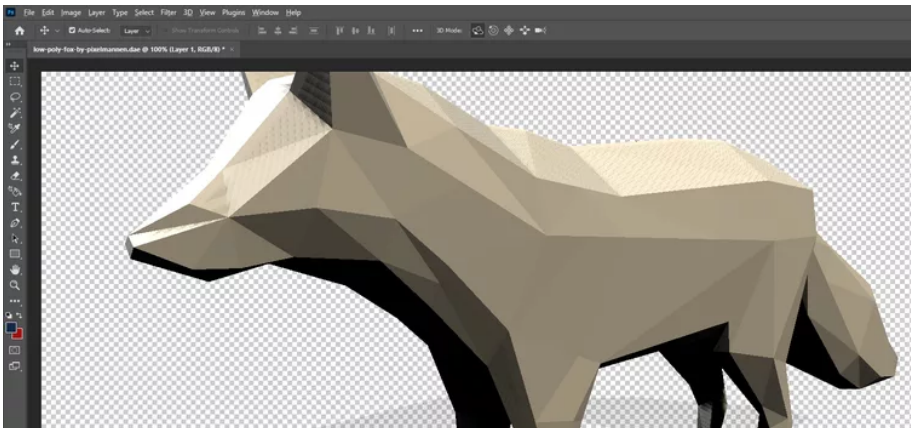


Figure 2.43: DAE file [42].

and insights. The foundation for the following research has been laid by identifying different approaches, obstacles, and advancements in the field through an examination of the current literature.

There is a need for a more effective and smooth information flow between BIM and VR, as evidenced by the investigation of existing approaches and technology in this regard. Although a great deal of progress has been achieved in with BIM and VR together thanks to existing technologies, a true bidirectional interchange of data and insights is still lacking.

The acknowledgment of the potential of BIM and VR integration to transform the design, construction, and management processes in the architecture, engineering, construction, and operation (AECO) industry is the driving force behind the investigation of the state of the art. Through the utilization of BIM and IFC for data-rich modeling and VR for immersive visualization, stakeholders may improve understanding, communication, and decision-making at every stage of the project.

Moreover, comprehending the present state of BIM and VR integration offers a framework for specifying the goals and parameters of the suggested technique. This research intends to contribute to the creation of a more reliable and useful method for utilizing BIM and VR technologies together by expanding on the developments and resolving the constraints found in the state of the art.

Chapter 3

Specification of the problem

The foundation for comprehending the project's needs is provided by the section on the Specification of the Problem in this work. It describes the particular problems, difficulties, or requirements the project seeks to solve and offers crucial background information for the ensuing stages of development and execution. We will explore the history and definition of the problem requirements in this section, providing insight into the people or teams in charge of directing the project and the method used to develop these specifications.

3.1 Elicitation

Defining the problem specifications usually need teamwork and the application of a variety of expertise, but in this case, the participants involved were Subject Matter Experts, more specifically, the teachers assigned to guide this project, one of them experienced in the area of civil construction and the other in the area of IT. These Individuals with deep domain knowledge and expertise are essential in providing insights into the intricacies of the problem and the nuances of potential solutions. Their contributions are instrumental in refining and ensuring the relevance of this project. Another participant would be market research and statistical analysis, looking at the minimum requirements and valuable features for stakeholders of existing products or projects.

3.2 Process

The process of defining the problem specifications involved the following steps:

- Problem Identification: The process begins with the identification of the problem or opportunity that the project seeks to address. This step involved discussions with with subject matter experts.
- Use Case Definition: Use cases are formulated to describe specific scenarios or interactions that capture the problem's essence. These use cases were refined through ongoing discussions and feedback from the subject matter experts.
- Prioritization: Not all possible cases or features were of equal importance. Prioritization was necessary to focus on the most critical and impactful features.

3.3 Use cases

The use cases presented in this specification have emerged as a result of a carefully orchestrated process and a thorough understanding of the domain in question. This use cases encapsulate the scenarios that the project or system is designed to address, ensuring that the final solution aligns with the practical needs of its intended final users.

The use case diagram was created to give a better perception of the system's functionality. A use case diagram is a visual representation that illustrates the interactions between users (actors) and the system being developed. It helps to identify and understand the different use cases or functionalities of the system. They help to capture and visualize the desired functionality and interactions of a system. They serve as a blueprint for the development process, ensuring that all stakeholders have a shared understanding of the system's requirements and behaviour.

Actors represent the many roles or entities that interact with the system. Users, external systems, or other stakeholders can all be actors.

Scenarios are in-depth accounts of specific interactions or series of deeds between actors and the system. They offer a story that aids in comprehending how the method is applied in practical circumstances.

Use case diagram define the system's functional requirements, detailing what the system must accomplish to meet the demands of its users, [23].

Construction professionals and clients will be able to:

- Import an IFC Base
- Move around the model
- Teleport
- Consult properties
- Edit properties
- Edit quantities
- Consult quantities
- Edit quantities
- Edit visibility
- Change opacity to semi-transparent
- Change opacity to invisible
- Select items
- Select one or more elements manually
- Select one or more elements automatically
- Change the color of materials
- Create a comment (BFC)
- Record in 1st person
- Cinematic recording
- Change the guest of an element
- Move elements
- Import secondary IFCs into the main IFC
- Delete elements

- Redo change
- Undo change

An use case diagram for this system can be seen in the Figure 3.1 below:

Looking at Fig. 3.1, the actor "Construction professional or client" is an individual, or a group of people who represent the possible users of this system. They can take advantage of the various functionalities, such as being involved in multiple activities: importing an IFC Base, moving around the model, teleporting, consulting properties, importing an IFC base, editing properties, editing quantities, querying quantities, editing quantities, change the opacity to semi-transparent, change the opacity to invisible select elements, select one or more details manually, select one or more elements automatically, select one or more elements automatically, change the color of materials, create a comment (BFC), record in 1st person, cinematic recording, change the guest of an element, move elements, import secondary IFCs into the leading IFC, delete elements, redo change, undo changes.

3.4 Proposed architecture

In this section, we introduced and covered some tools that served as the cornerstone of the proposed architecture. However, when considering the particular objectives and difficulties the study addresses, the reasoning for choosing these tools becomes more evident. Section 4.1 provides a thorough knowledge of the strategic factors and subtle motivations that influenced our decision-making process and led us to conclude that these tools were the most appropriate for achieving the objectives.

During the course of this work, two approaches were followed: one that follows the direction of AutoDesk Revit present in the Figures 3.2 and 3.3 and the other with the use of a conversion tool "IfcConvert" in Unity, that can be seen in the Figures 3.4 and 3.5.

The first draft (Figure 3.2) of the methodology was based on converting a BIM model in Autodesk Revit to the Unity game engine. This is possible without external help. By exporting the FBX file to Unity, the scale fits perfectly in Unity (1:1) and the GameObject hierarchy as the element hierarchy in the model is well organized, but it comprises meshes that are called according to their Family type and include the specific Revit Entity ID in brackets. The model's shape is accurate. However, the material details still need to be included. Even worse, there is no unique assignment of materials to certain meshes, so it result in a flat gray model.

Additionally, the mapping is useless when manually allocating materials with textures. The required UV coordinates are missing from the geometry imported into Unity. In Unity, this is difficult to address unless scripts to edit or generate UV coordinates are used. So in overview when exporting FBX to Unity from any 3D modeling software, it gets the model, the mesh, and the rigging. All the materials assigned are returned in the modeling software, but these are all considered default Unity materials. A possibility would be to import the textures used in Unity, create materials with those textures, and use them in the imported model is needed, but that would go against the automation of this process.

Investigating other options to load models from BIM to Unity. Looking for other 3D formats which can be recognized by Unity, such as DXF, OBJ, 3DS, DAE, and FBX, this files are discussed in the state of art Chapter 2.

Of these files represented here, the FBX type file and the Collada (DAE) file, are perfect for importing their geometry. But the FBX file, after import does not show material information, all elements use a material without texture. In the case of DAE, no material is retained by Unity. In the 3DS file after import the elements, they are confused, and without any grouping. The DXF file type does not use textures either. So by elimination, what remains is the OBJ file type, this file is perfect for presenting the geometry in Unity.

So, to have a bit of both worlds, the second draft (Figure 3.3) appeared, and, from there, it was analyzed how it was possible to bring in geometry materials automatically without analog help, which led to the discovery of the MTL file type, this being a material configuration file for 3D modeling.

But this does not present the necessary information transfer of the elements present, this being fundamental to achieve the objective of information exchange between the BIM models, and the virtual environment models.

Utilizing the Industry Foundation Classes, or IFC, a format designed to record geometry and information is an additional choice and a solution for the information exchange. And BIM software accepts the format, Unity would not, by default, support it.

With this in mind, it was examined how to provide a method of manipulating the IFC file in Unity, given that necessary exporting and importing is already possible using BIM tools. It would take a lot of time and effort to accomplish many of the proposed objectives if there were a lot of searches made in the AssetStore for Unity pre-existing tools that were free, and even if there were searches made to create a rake import script that was abandoned after some time because it was time-consuming and challenging to complete. Concerning examining other research and via research, a tool created by IfcOpenShell Open Source was discovered. The reverse procedure had to be carried out as soon as the relationship between the BIM and Unity was complete. The manipulation of the IFC file was sufficient for this purpose, so the next step was to determine whether any libraries existed that could be used to manipulate the IFC, such as the XBIM library. As a result, the chosen methodology was reached as shown in Figure 3.4, in which it was possible to extract geometry, material, and information files for Unity with the XBIM library. This information file is centered in the XML file, this file defines and store data in a shareable manner, that supports information exchange between computer systems such as websites, databases, and third-party applications. With this done, it is possible to see the possibilities shown in the Figure 3.5 since an externally sourced IFC can come from the internet or another source or internally for its creation in a BIM application like Revit.

In overview this methodology (Figure 3.4) illustrates the import of OBJ, MTL, and XML files into Unity, where Unity serves as a viewer, and as a support for editing the IFC schema, where then the conversion of the IFC schema into OBJ, MTL, and XML files is done using a converter, and then importing them, always in this cycle, when any changes have been made.

In order to be able to edit the IFC schema, a .NET based library "XBIM", that is open source, and usable in Unity was used.

Initially the approach would be to enable the export of a BIM model, in Autodesk Revit through an API made by the author to the game engine, and vice versa (Figure 3.3), but this was changed to an approach where users who do not have in their possession the Autodesk Revit software, can import the BIM model in IFC schema to the game engine (Figure 3.4), and this IFC schema can be obtained by exporting in several tools, as well as downloading on the Internet, without the use of any tool (Figure 3.5).

The methodology for the development of the Framework claims the main objective to make the connection, and transfer of information between the BIM modeling software and the game engine.

3.5 Process/Procedure

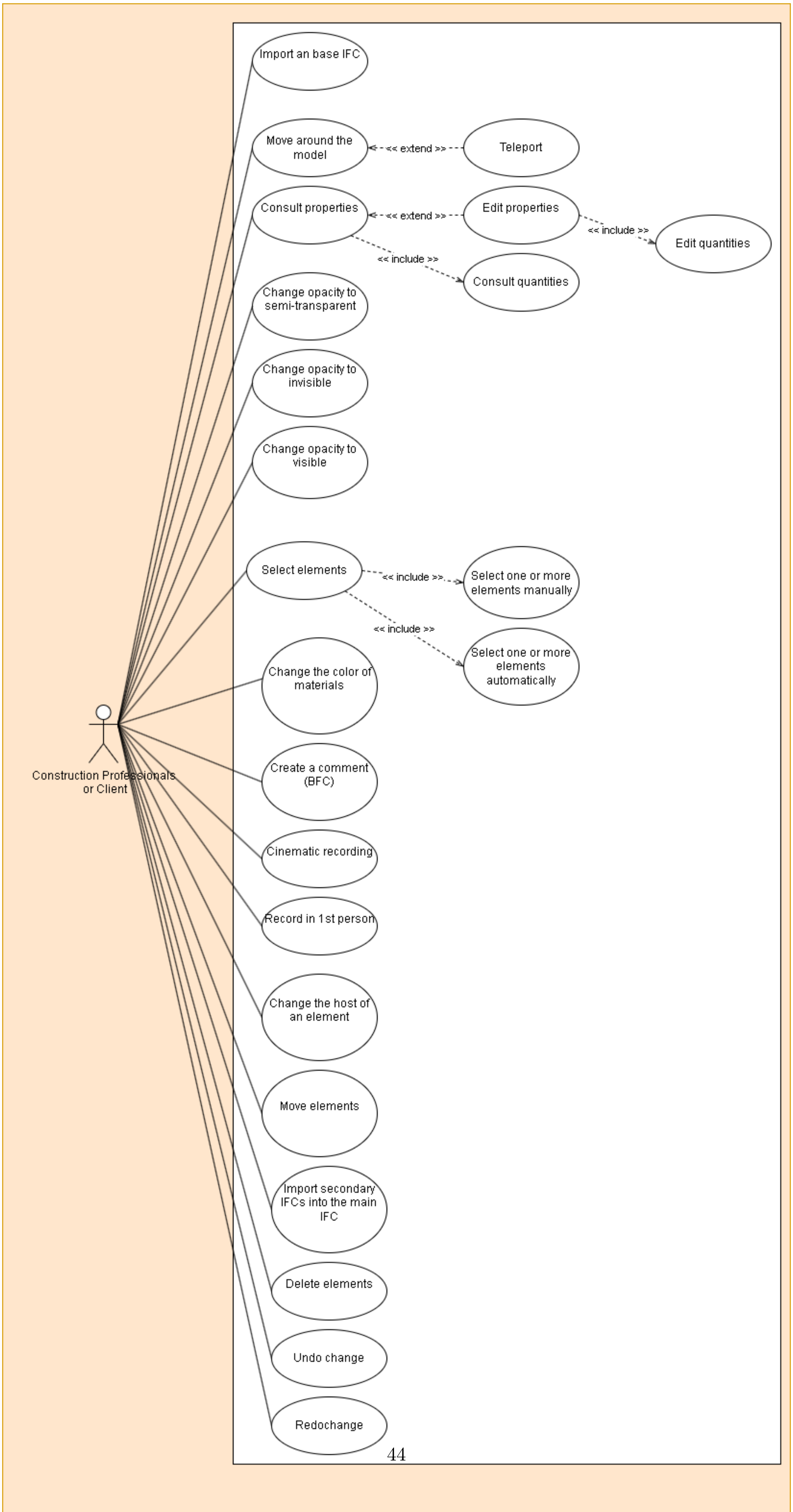
The development method chosen was the methodology specified in the last section 3.4. So to be able to do this, a planned and meetings were necessary, with a fresh prioritization of the needs to be built in the sprints is created at the end of each cycle of the development process after the implementation of the prioritized requirements. New criteria were solicited and prioritized throughout the process when they changed in response to achieve the objectives.

According to the BIM software aproach (Figure 3.3), the API was implemented using a Revit plugin, as Autodesk Revit itself supports the creation of plugins. This plugin was created in C-Sharp using the Visual Studio Community resource. Therefore, installing the Revit dependencies to function without any problem when run by Revit was optional. This plugin aimed to export all elements in a view for printing in OBJ and MTL. Later on in Unity, it was possible to import the same thing using an item available in the Store of Unity. In particular, "Runtime OBJ Importer" allows for the import of the OBJ model and can load all materials and textures from streams, all of this in Unity's runtime, what is essential for what we want to do. This draft, made the information exchange not possible, which leads to the use of IFC schema.

Moreover, the adopted methodology present in Figure 3.4, the IfcConvert tool replaced the API, requiring only an IFC file and the execution of commands; in this instance, the commands would be to split the file into three files. The IFC schema information is simplified into a tree with its proper hierarchy and with the properties or the set of the elements, similar to the previous draft, which included an OBJ file with geometry, an MTL file with materials, and an XML file. This XML file only serves as a help to visualize and retrieve the information of the elements more quickly because the IFC is a bit confusing in which we have all the materials geometry and which use the STEP structure, the transportation on itself is expensive to conduct any kind of research.

A C-Sharp-based library was used to wrap up the information transfer cycle in the Unity editing section concerning the library's documentation. The same code is combined with the game engine's required code, permitting any changes to the visualizer, in this case, the Unity model, to be reflected in the IFC file, which would then be reimported into the Unity model with the changes made (Figure 3.6). In this way, we would never experience issues with synchronization because the model would always be a part of the IFC file, which serves as the foundation for communication between the two sides. This approach was chosen since manipulating the vertices and faces in Unity is complicated so that the model can be exported for in OBJ later, for example.

In order to make all of this, two version of the project was performed, one concentrated on the use of the mouse, and the keyboard, for the first version of the project and the last version was the implementation in virtual reality. This VR version contains a guide found in the Appendix Chapter J for its installation and controls, whether with the HMD or with the keyboard and mouse, if the HMD is not connected.


Construction Professionals or Client
Import an base IFC
Move around the model
<< extend >>
Teleport
Consult properties
<< extend >>
Edit properties
<< include >>
Edit quantities
<< include >>
Consult quantities
Change opacity to semi-transparent
Change opacity to invisible
Change opacity to visible
Select elements
<< include >>
Select one or more elements manually
<< include >>
Select one or more elements automatically
Change the color of materials
Create a comment (BFC)
Cinematic recording
Record in 1st person
Change the host of an element
Move elements
Import secondary IFCs into the main IFC
Delete elements
Undo change
Redochange

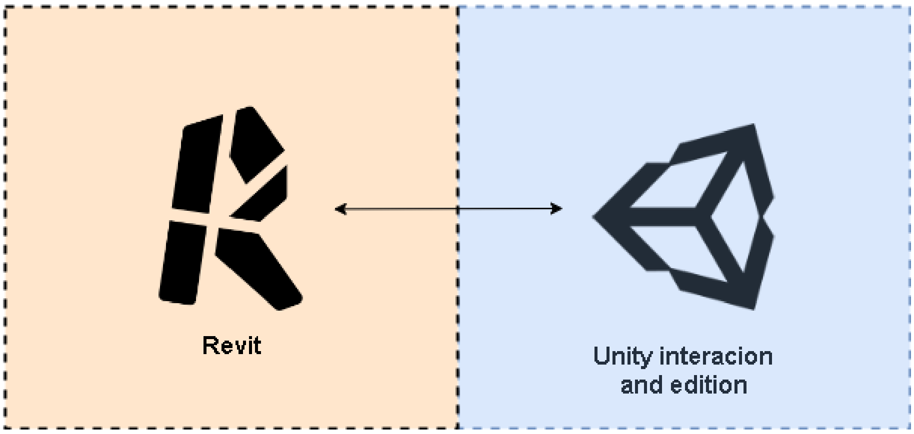


Figure 3.2: First draft of the methodology- Simple communication.

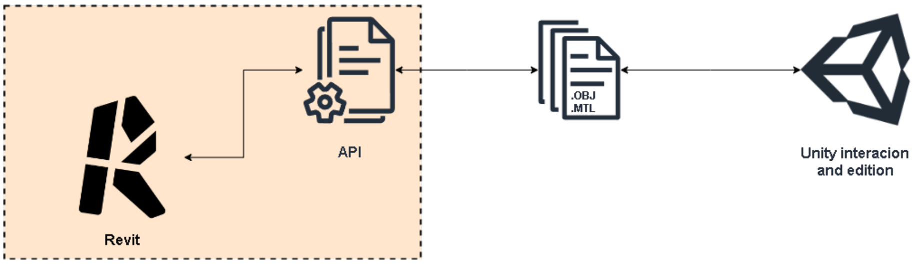


Figure 3.3: Second draft of the methodology- Communication with the help of an developed API by the author.

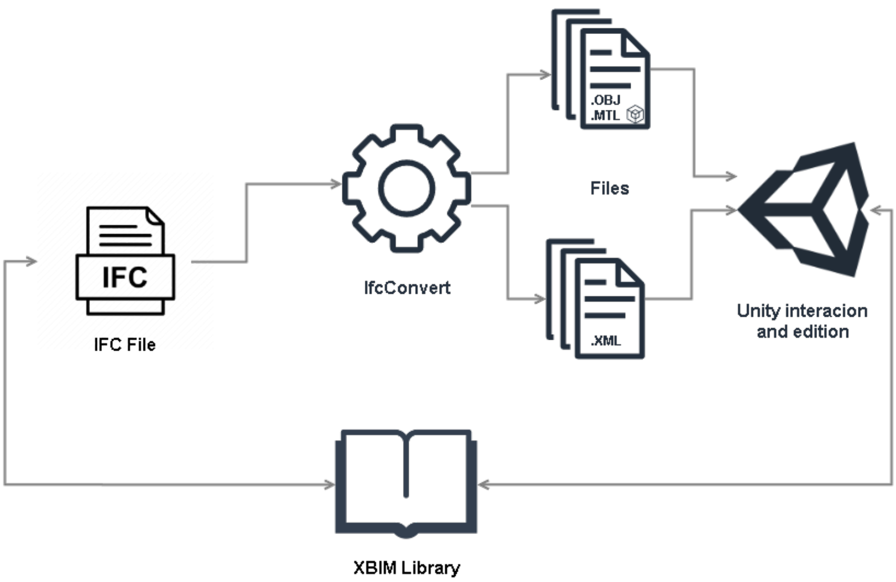


Figure 3.4: Flowchart of the methodology adopted- Bidirectional communication achieved.

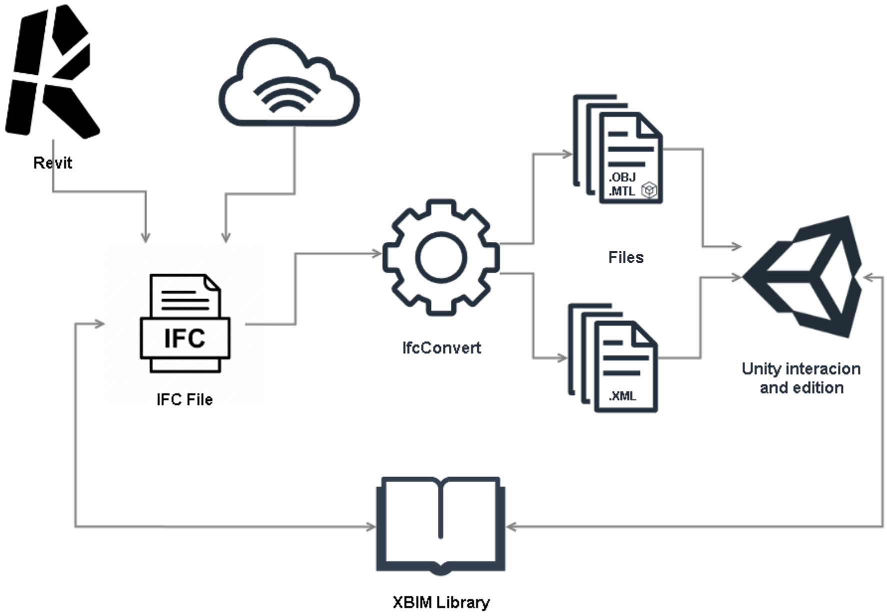


Figure 3.5: Possibilities with the adopted methodology.

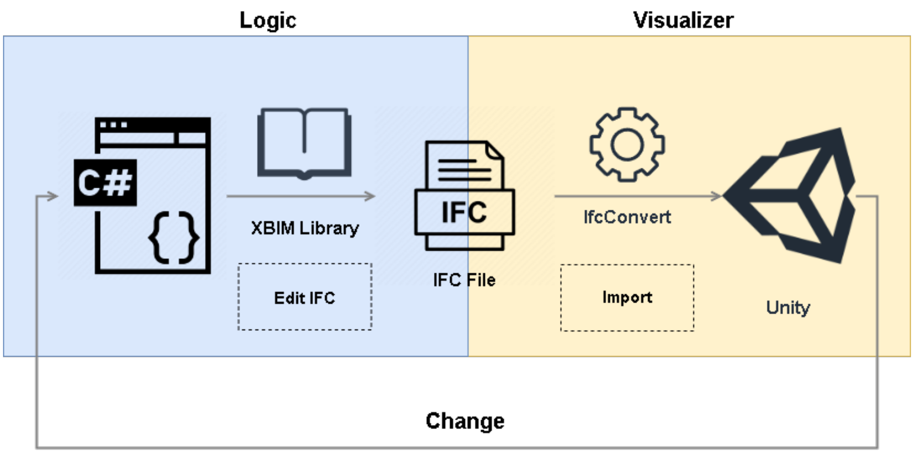


Figure 3.6: Logic of the bidirectional communication between Unity and BIM

Chapter 4

Implementation and Development of the solution

This chapter covers all aspects of the system's implementation, including the chosen technology, BIM software and GameEngine efforts, as well as the tools and technologies that supported its development talked about in the previous section 3.

4.1 Selected Tools

4.1.1 Technology

Although each technology has its strengths, VR has certain advantages that can make it superior in this context:

- Immersive experience: VR provides the most immersive experience, transporting users to a different environment. The feeling of "presence" in VR has been widely studied, demonstrating its potential to increase engagement and learning [86].
- Training and teaching skills: VR is proven effective for training because it creates realistic simulations and scenarios. Medical training, pilot training, and the operation of complex machinery can all be done better in VR, [106].
- Design and creativity: VR allows engineers, designers, architects, and artists to visualize and interact with their creations in 3D space, increasing creativity and enabling rapid prototyping, [26].

We have this technology in therapeutic applications, having been used in exposure therapy for the treatment of phobias, post-traumatic stress disorder (PTSD), and anxiety disorders. Its controlled and immersive nature allows for safe exposure to triggering situations, [63].

On the other hand, the need for dedicated hardware, potential motion sickness, and limited awareness of VR's physical environment can be drawbacks.

There are four main areas of a VR simulation that can benefit BIM platforms: Visualization, Navigation, Interaction/Manipulation, and Socialization (such as cooperation and learning) [8][51][97].

In conclusion, although VR offers unparalleled immersion and transformative potential in various domains, according to the objectives of this work and the objectives of the users, this technology best fits the intended application.

4.1.2 Hardware

Because of its sophisticated features, compatibility, and suitability for immersive architecture visualization experiences, the Oculus Rift S present in Figure 4.1 was selected as the hardware platform for the created virtual reality application. Users interacting with architectural models and virtual surroundings can enjoy engaging and immersive virtual reality experiences because to its inside-out tracking technology, high-resolution screens, and user-friendly design.

Figure 4.1: Oculus Rift S [67].

4.1.3 Software tools

4.1.3.1 BIM software

The chosen technology was Revit software because of its extensive features and adaptability. It is regarded as the finest software for connecting BIM with VR. Users of Revit may quickly convert their 3D models into a VR environment, allowing them to view their designs in an immersive manner. This function is crucial for architects and designers who need to envision their projects more realistic and dynamic.

The capability of Revit to produce precise and thorough 3D models is one of its main benefits. Because it enables architects and designers to construct incredibly intricate and realistic surroundings, this capability is beneficial for producing VR experiences.

Due to Revit's high adaptability, users may design distinctive processes and customize the program to meet their requirements. This flexibility is crucial for architects, engineers operating in diverse sectors with varied project needs, and for the purpose of this project.

Revit was the the chosen software for connecting BIM and VR because of its extensive capabilities, adaptability, collaboration tools, connectivity with other programs, and customizability.

4.1.3.2 Game Engine

When choosing a game engine for VR development, Unity and Unreal are two significant players in the market. Both machines have their strengths and weaknesses, but the chosen was Unity as the game engine for the VR development of this project.

It was chosen because Unity is known for its user-friendly interface and ease of use. Additionally, Unity has a large and active community, making it easier to find support and resources when you encounter challenges during development. Unity has a vast and diverse Asset Store, with a wide range of pre-made assets, scripts, and plugins to enhance the VR development process. This can save time and effort by allowing you to leverage existing resources and focus on the unique aspects of the VR project.

Also, Unity primarily uses C-Sharp as its scripting language, which made the Unity scripting system easy to learn.

4.1.3.3 Other tools

Various software tools were used throughout the project to help develop the system. The Visual Studio Community, GitHub, usBIM.viewer+, xBIM viewer, XBIM library, accasoftware, and OCULUS app contributed to different parts of the project. The functionalities of each tool are as follows:

- Visual Studio Community: An integrated development environment (IDE) offered by Microsoft that provides developers with a powerful set of tools for creating a wide range of applications, supporting multiple programming languages, including C++, and Python, and C-Sharp that was main language in this project.
- Github: A web-based platform for collaborative software development. It is an essential tool for developers and companies throughout the world since it makes code management easier, promotes cooperation, and encourages open-source contributions. This tool was chosen for the version control of the project.
- Oculus App: An application developed by Meta for managing and interacting with Oculus VR devices, this app was used to apply different settings for a better VR experience.
- usBIM.viewer+: For viewing and interacting with BIM Models, this software enables users to visualize and explore BIM data and models, aiding in construction and architectural project analysis and collaboration.
- xBIM viewer: An open-source software tool that was manly used for viewing BIM in various formats. It provides a user-friendly interface to visualize and navigate BIM data, making it valuable for architects, engineers, and construction professionals.
- XBIM library: An open-source software framework for BIM applications. It provides developers with a set of tools and APIs to work with BIM data, facilitating the creation of BIM software solutions and interoperability in the construction and architectural industries, this framework was used to manipulate the IFC file, the section 2.9 gives a little more details about this library.
- Accasoftware: An online software that allowed to open, edit and update BFC files, this software came in handy because it could test if the generated BFC file from the project was correct.

4.2 VR application

This subsection will explain the properties of this VR application as their explanation as well as describe the implementation of the two different versions, the computer-based version and the VR-based version, and then the existing features in the application. Both will have almost the same functionalities since the virtual reality version is the passage of the functionalities of the computer version to the virtual reality with attention to the user interface.

4.2.1 Properties

To guarantee a smooth and practical experience, this VR application that permits two-way communication between Building Information Modeling (BIM) software and the virtual reality environment must have specific properties. The following essential characteristics of such an application, together with their significance, are listed:

- Synchronization: The VR program needs to stay in sync with the BIM model. This guarantees that any modifications made to the BIM program will be mirrored in the virtual reality setting. Synchronization is essential for precise decision-making and design evaluation. This synchronization isn't in real time because each time a change is made, the model is refreshed in the VR program, which can cost a bit of time depending on the IFC file size. In other words, at an initial stage, the model is imported into the virtual environment, and when any changes occur, the changes are made to the IFC file using the XBIM library using scripts, which, after the file is updated with the changes, is imported again. to the virtual environment, thus maintaining synchronization.

- 3D Model Integration: The program enables the importation of 3D models made with BIM applications. These models can have a great deal of detail, including details about the equipment, materials, and structural components. For a realistic experience, the VR environment needs to render and show these models appropriately.

- Data integration: BIM models frequently include helpful information about building elements. To give users information about the objects they interact with in the virtual environment, this VR application facilitates the extraction and display of this data. Design analysis, maintenance, and documentation can all benefit from this data linkage with the help of the XML file.

- Interactive Elements: Users can interact with BIM elements within the VR experience. In order to allow designers and stakeholders to make changes and annotations, this interactivity can include moving, change colour, delete, and change visibility.

- User-Friendly Interface: For non-technical stakeholders and BIM specialists, an intuitive user interface is essential. It should be possible for a diverse variety of users, such as architects, engineers, project managers, and clients, to operate and navigate the VR application efficiently.

- Cross-Hardware Compatibility: This VR application is compatible with different hardware, in this example, with the keyboard and mouse. This ensures that stakeholders can use their preferred or available hardware.

- Immersion: It describes how much a user feels wholly present and engaged in the virtual environment. To make a VR experience that is both believable and engaging, intense immersion must be achieved. This feature is essential for giving consumers the impression that they are inside the virtual world and can forget about the real one.

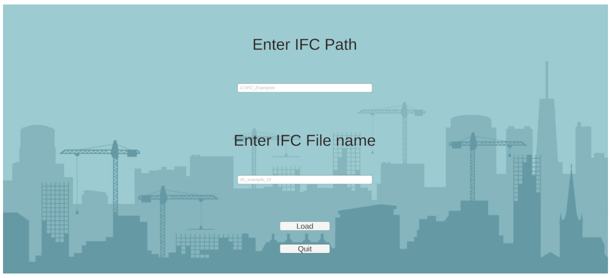
  Presence: The feeling of "being there" in the virtual environment is synonymous with immersion. Users should be able to engage with and traverse the virtual environment as if it were genuine, thanks to VR applications that give them an intense sensation of presence. This quality is essential to producing an engaging and lifelike virtual reality experience.

- Comfort: To avoid motion sickness and discomfort, this VR application needs to take user comfort into account. To prevent adverse effects and guarantee that users can enjoy the VR application for extended periods, proper calibration, user-friendly interfaces, and well-designed user experiences are crucial.

4.2.2 Interface

In terms of the interface, the two versions differ greatly, for example in the computer version there are two scenes, the first being a menu where you are asked for the data of the IFC file to be imported based on the path and name of the file (Figure 4.2a), and in the VR version only one scene where you are first asked for the IFC file based on the file system (Figure 4.2b).

The interface in the computer-based version aims to be simple and is based on buttons and text on the edges of the screen, unlike the VR-based version in which an interface was designed on the wrist as if it were a watch, in which in this interface a plane was arranged serving as a menu and later this menu could have extensions (Figure 4.4), a comparison between the interface of the two versions can be seen between the Figure 4.3a and 4.3b.



(a) Computer based- Main menu, where it asks for the information needed to import the IFC schema.

(b) VR based- Importation of a IFC file by file system.

Figure 4.2: Importation of a IFC schema model in the different versions.

Both versions were designed to be simple and easy to understand. Efforts were more focused on the VR version, since this was the final version and the computer-based version was a prototype.

4.3 Communication IFC file/game engine

To import the IFC file into the VR model with its appropriate geometry, information and materials, the IfcConvert tool was used. With its ability to only specify an input and output file, the file extension provided in the input determines what format the IFC is converted to, and creates it as output.

The following prompt is an example of how we could use it using the command line.

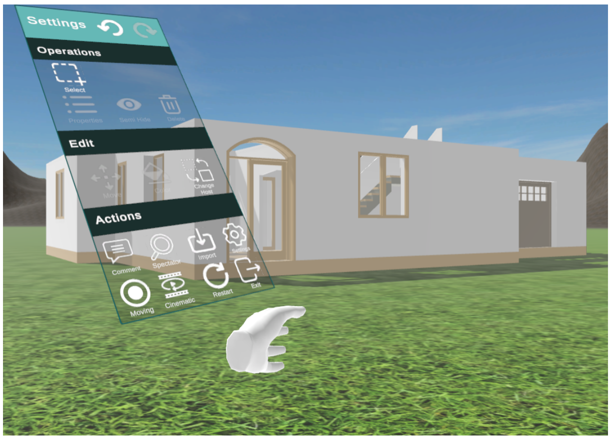
```
$ IfcConvert /path/to/input.ifc /path/to/output.obj
```

This prompt was run from Unity with the help of the processes functionality.

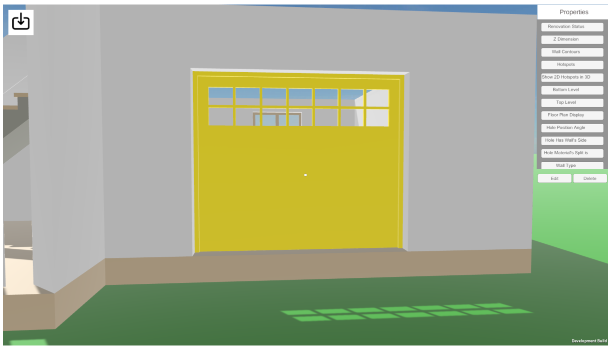
When you run this command, the input ifc file is converted to an OBJ output file at the specified path. The Code snippet above, depicts the execution of a process by command using the IfcConvert tool in C-Sharp code where in the input target the file extensions vary between .obj, .xml and .mtl, the input will always be the IFC file i.e. with the extension .ifc.

An example of the use of this function can be seen in Figure 4.5, where after executing the function three times for each of the extensions, the three result files from the IFC file are obtained.

For the other side of the communication, the manipulation of the IFC file with the XBIM library is necessary to convert the IFC file again in the OBJ and MTL files, an example of the use of this library can be seen in the following code snippet in Figure 4.6.



(a) VR based interface.



(b) Computer based interface.

Figure 4.3: Different interfaces of the two versions.

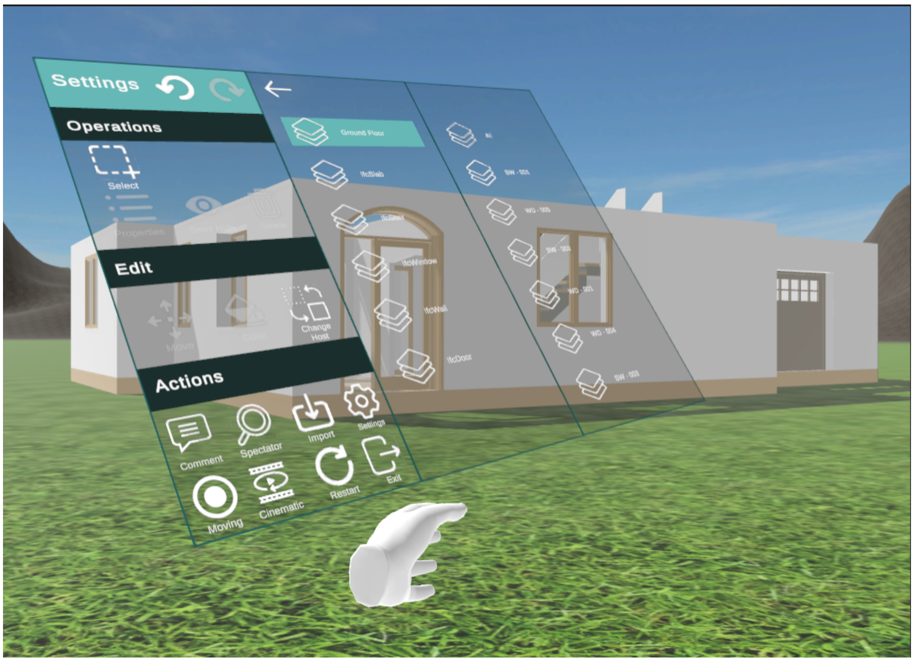


Figure 4.4: Multiple panels in the VR interface

4.4 Functionalities

This section describes the features in the system developed, focusing on the innovative features in the VR version. The features in the Computer version compared to the VR version are the same, with the exception of the VR features, such as teleportation.

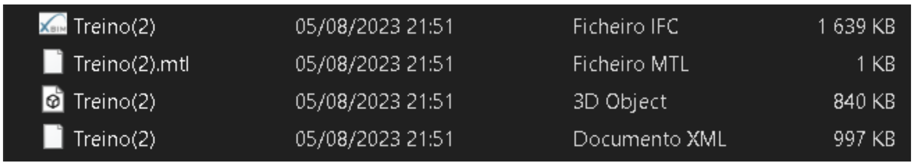


Figure 4.5: Result of the IfcConvert tool.

```
var editor = new XbimEditorCredentials
{
    ApplicationDevelopersName = "xbim developer",
    ApplicationFullName = "xbim toolkit",
    ApplicationIdentifier = "xbim",
    ApplicationVersion = "4.0",
    EditorsFamilyName = "Santini Aichel",
    EditorsGivenName = "Johann Blasius",
    EditorsOrganisationName = "Independent Architecture"
};
using (var model = IfcStore.Create(editor, IfcSchemaVersion.Ifc4, XbimStoreType.InMemoryModel))
{
    using (var txn = model.BeginTransaction("Hello Wall"))
    {
        //there should always be one project in the model
        var project = model.Instances.New<IfcProject>(p => p.Name = "Basic Creation");
        //our shortcut to define basic default units
        project.Initialize(ProjectUnits.SIUnitsUK);

        //create simple object and use lambda initializer to set the name
        var wall = model.Instances.New<IfcWall>(w => w.Name = "The very first wall");

        //set a few basic properties
        model.Instances.New<IfcRelDefinesByProperties>(rel => {
            rel.RelatedObjects.Add(wall);
            rel.RelatingPropertyDefinition = model.Instances.New<IfcPropertySet>(pset => {
                pset.Name = "Basic set of properties";
                pset.HasProperties.AddRange(new[] {
                    model.Instances.New<IfcPropertySingleValue>(p =>
                    {
                        p.Name = "Text property";
                        p.NominalValue = new IfcText("Any arbitrary text you like");
                    }),
                    model.Instances.New<IfcPropertySingleValue>(p =>
                    {
                        p.Name = "Length property";
                        p.NominalValue = new IfcLengthMeasure(56.0);
                    }),
                    model.Instances.New<IfcPropertySingleValue>(p =>
                    {
                        p.Name = "Number property";
                        p.NominalValue = new IfcNumericMeasure(789.2);
                    }),
                    model.Instances.New<IfcPropertySingleValue>(p =>
                    {
                        p.Name = "Logical property";
                        p.NominalValue = new IfcLogical(true);
                    })
                });
            });
        });

        txn.Commit();
    }
    model.SaveAs("BasicWall.ifc");
}
```

Figure 4.6: Example of creating a wall with the XBIM library.

4.4.1 Import a base IFC

As seen in the previous section, as seen in Figure 4.3a, importing an IFC file as a base is done right at the program's beginning. The selection of IFC files is done through a file system based on the Windows File Explorer file system, with the default path being the C disk. It even contains quick shortcuts based on the most common directories on your computer. This file system only lets you open folders, has file extension filters, and only lets you load IFC files.

4.4.2 Teleport

This feature allows you to use teleportation to move around the virtual model better. The Teleport is made to the blue area in Figure 4.7. This area comes from a ray from the left controller that can be activated or deactivated.

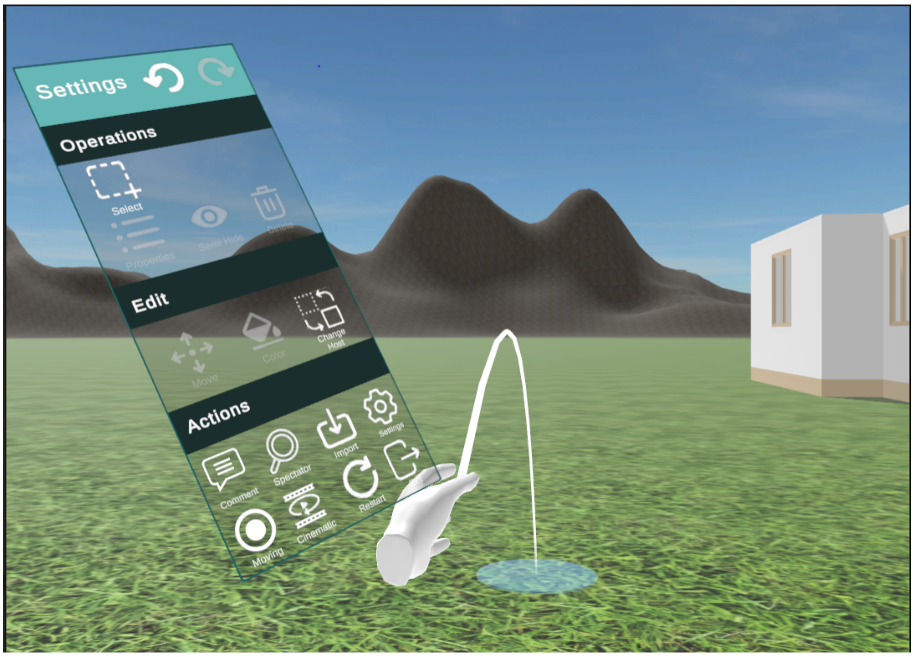


Figure 4.7: Enabling the teleport functionality.

4.4.3 Properties of the elements

The functionalities present in properties can be divided into two, specifically in viewing and editing properties. These properties can be of two types, more specifically, the property type and the quantity type. This functionality is only possible by selecting a single element in the model. Editing properties is done with the support of the XBIM library, which sends the change directly to the file by script making any change as a new save, a new file. Changing the quantity properties does not change the element's geometry, and they are not automatically calculated when editing the model. These quantities only come from the Revit software, for example. Editing the properties is done using a virtual keyboard, as using a physical keyboard would be inconvenient. Interaction with the keyboard is shown in Figure 4.8.

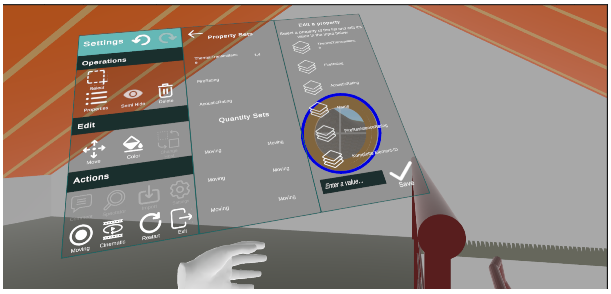
In Figure 4.9a, it's possible to see the window properties; in Figure 4.9b, the change in the value of the FireResistance property to the value "3" is visible.

4.4.4 Change visibility

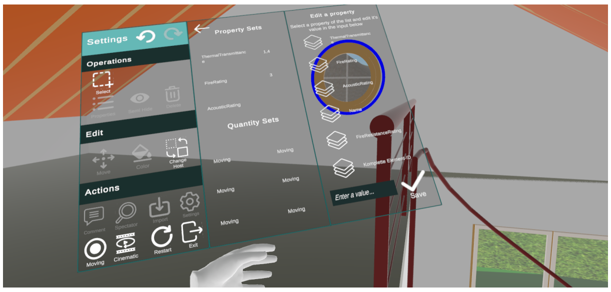
It is possible to change the visibility of one or more elements. This visibility has three types, namely:

- Normal: Visibility with 100 percent opacity is what it is by default (Figure 4.10a).
- Semi-invisible: Less than half the normal opacity of the element(s), it is perfect for knowing that there is a wall, for example, but seeing inside it (Figure 4.10b).
- Invisible: Opacity of 0 percent, totally invisible but still subject to collisions, meaning the element is not deactivated (Figure 4.10c).

Figure 4.8: Use of the virtual keyboard

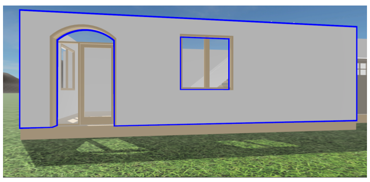


(a) List of properties and quantities of an element.

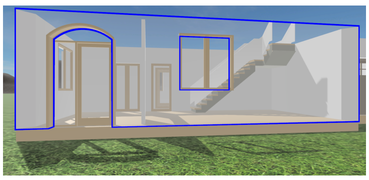


(b) Edited property

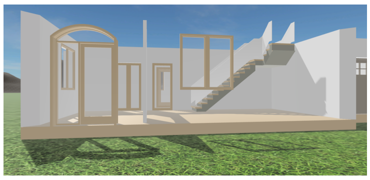
Figure 4.9: Visualization and editing of the properties of an element in the model.



(a) Element with normal opacity.



(b) Element with half opacity.



(c) Element full invisible.

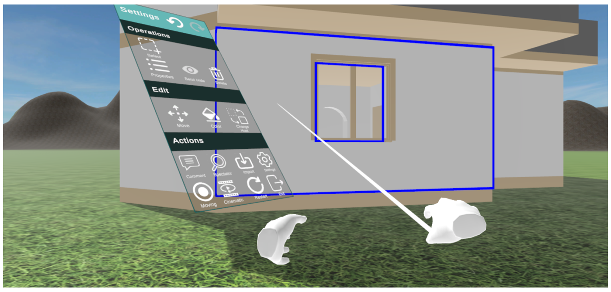
Figure 4.10: Change of the opacity of an element

4.4.5 Element Selection

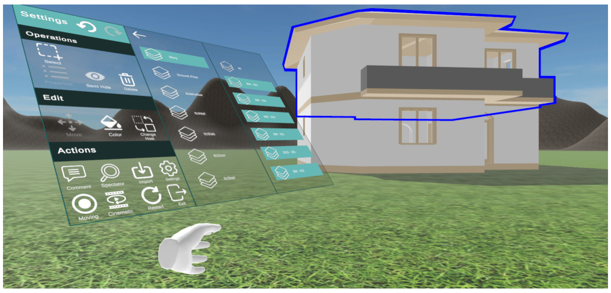
Regarding the selection of elements, when selecting an element, its outline is shown in blue to highlight what can be seen in the Figures 4.11a and 4.11b. This selection has two forms: manual and automatic.

4.4.5.1 Manual Selection

For manual selection/deselection of one or more elements, the user will need the element with the controller pointed at the element until a white ray appears. When this ray appears, it indicates that it can be selected using the button. Corresponding selection on the controller. An example of a manual selection



(a) Manual selection to an element.



(b) Multiple automatic element selection.

Figure 4.11: The two types of element selection.

can be seen in Figure 4.11a, where only one element is selected.

4.4.5.2 Automatic selection

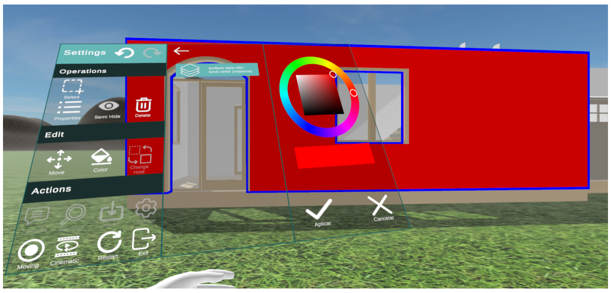
To carry out an automatic selection if the elements are outside the reachable limit or even if it is the case of selecting several elements of a type or even all the elements of a floor, the automatic selection is used for this. To carry out the automatic selection, first is needed to select the option "Select" in the main panel, and then panel is presented to the user in which he can select the floor or the type of element required. Subsequently, another panel is offered to select the element(s). An example of these panels and this type of selection is visible in Figure 4.11b, which represents the selection of the top floor of the model, in this case, the "Story" floor.

4.4.6 Change Color

To change the color of one or more elements, their prior selection is necessary. When choosing the color change option, a panel is presented as an extension in which you are asked to select the material to be edited, as the element can have several materials, or several colors in it. After choosing the material, a pallet-like system is presented to the user where it is possible to choose the color tone, and at the same time view its preview of the selected color (Figure 4.12a). After applying the color to the element, the model is imported with the change already made (Figure 4.12b).

4.4.7 BFC

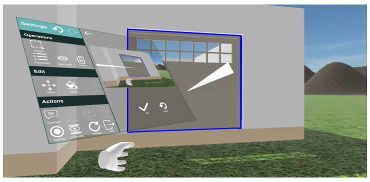
When creating a BIM Collaboration Format (BFC) file, a screenshot is taken by taking the UI from the screenshot view, and then an confirmation panel is shown to confirm the screenshot (Figure 4.13a), with the confirmation subsequently, the BFC form is filled out with an attachment to the screenshot taken (Figure 4.13b). The screenshot and this generated BFC file are saved in the IFC's base folder of the project (Figure 4.13c). Figure 2.7 shows an example of a BFC generated by the project in a usBIM online BFC viewer.



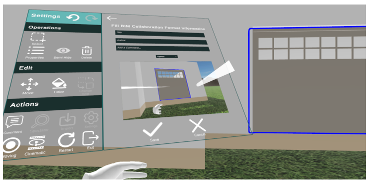
(a) Preview of the selected color on the selected material of an element.

(b) Change of the color applied to the element.

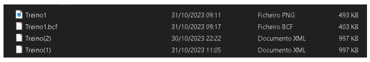
Figure 4.12: Change of the color functionality



(a) BFC- Confirmation of the screenshot.



(b) BFC- Form with information.

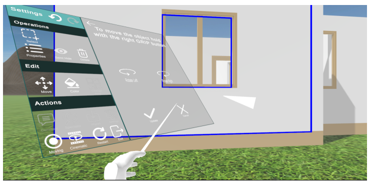


(c) BFC- Generated BFC file and screenshot in the IFC folder.

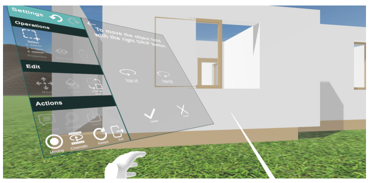
Figure 4.13: Creation of BFC file.

4.4.8 Move elements

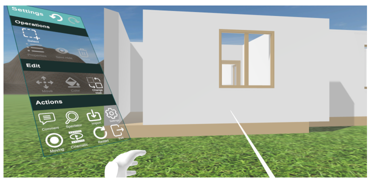
This functionality only exists if the selection is unique, and this functionality works by pressing and holding a specific button on the controller as if it were a manual selection and then dragging the controller to change direction, that is, with a drag-like movement. An example of this functionality can be seen in Figures 4.14a, 4.14b and 4.14c, with the before, the drag and finally the commit of a moved wall in a model.



(a) Selected a hosting wall to be moved.



(b) Dragging the selected wall to the desired location



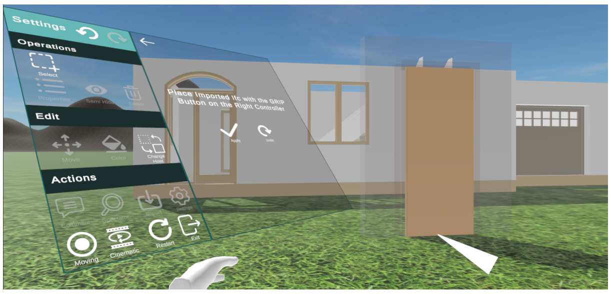
(c) Move to the wall applied.

Figure 4.14: Move functionality of an element.

Elements can be of type guest or have a guest. If the element is of the guest type, its hosts are moved in conjunction with it, unlike the elements in the guest. These already move by themselves. For example, when moving a wall with a window, the window is moved close to the wall, respecting its location towards the wall, unlike if it were to move the window, the change of place would only affect the distance within the wall.

4.4.9 Import objects into the main IFC

The possibility of importing secondary IFCs based on the original IFC is possible with this functionality by loading the IFC with the file system used for the original base IFC, after which the IFC is imported into the model with a preview of where it will look as we can see in Figure 4.15a. The user chooses the location, and when satisfied with the preview and confirmation, the model is reimported with the new IFC in the model (Figure 4.15b). This import brings not only the geometries but also the IFC information.



(a) Preview of the placement of the imported IFC.

(b) Commit of the imported IFC.

Figure 4.15: Import secondary IFC functionality.

4.4.10 Change of host

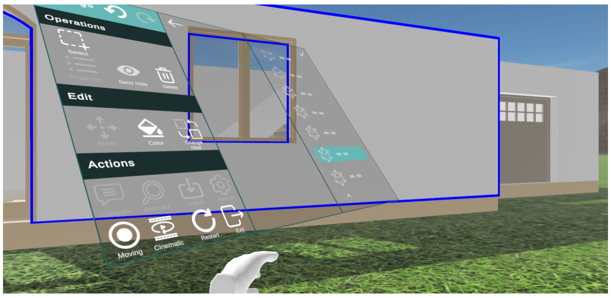
To change the host, selecting a previous host element is just a help, as this functionality requires one or no chosen element, as it presents two panels where, on the left side, you can select the list of possible elements to be hosts, and on the right side, the list of host elements. In the example in Figure 4.16a, the guest had already been previously selected, being the port imported from a figure in the previous subsection (Figure 4.15b). After applying the element, it is usually positioned a little further to the left of the host's geometry centre (which can often be at the ends of the elements), as shown in Figure 4.16b. After the host change, the location change can be made.

4.4.11 Delete

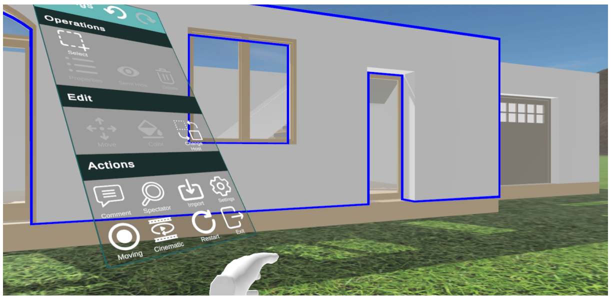
When deleting elements, this option can be single or multiple. Still, after selecting and choosing the delete option, a confirmation is requested from the user to confirm the deletion, as you can see in Figure 4.17a. After confirming, the element is removed from the element as seen in Figure 4.17b.

4.4.12 Undo/Redo

This Undo and Redo functionality is handy if an error occurs or you return to the original state. The arrows on top of the user menu panel control this functionality. If the arrow is greyed out, it means that the corresponding action is not possible. An example of this functionality can be seen in Figure 4.18, in which the user undoes the Delete action on the element in the subsection above (Figure 4.17b) and then redoes it, returning to the state of Figure 4.17a.

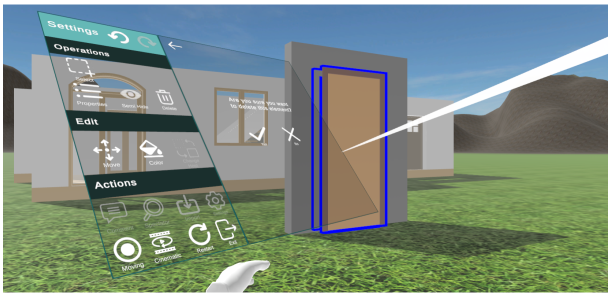


(a) Change host of an element interface.

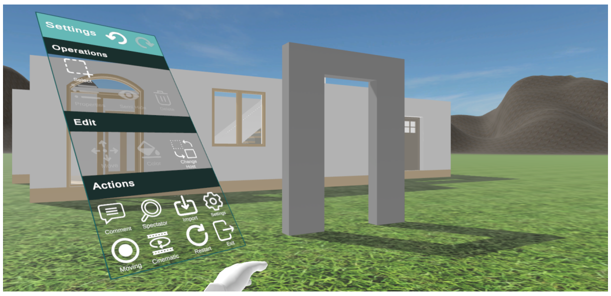


(b) Commit of the host changes.

Figure 4.16: Change host functionality.



(a) Delete of an element confirmation.



(b) Model without the deleted element.

Figure 4.17: Delete functionality.

In technical terms, this functionality has no limit on redo or undo actions, it is all on a file basis, in each change, there will be a new file, that is, taking an original IFC file and making changes to it, a copy of the previous IFC is created with the change made, and if it is Once the redo or undo action is performed, the model imports the copy of the next or previous file, a visual example is seen in Figure 4.19, in the different copies of the IFC file "Task-4", in which two was done changes to the model, thus preserving the original file as well as each change made.

4.4.13 Record a video

There are two forms of recording: first person, that is, from the user's perspective, and cinematic. These features generate videos in MP4 files, which are saved in a folder at the IFC's file path with the name of

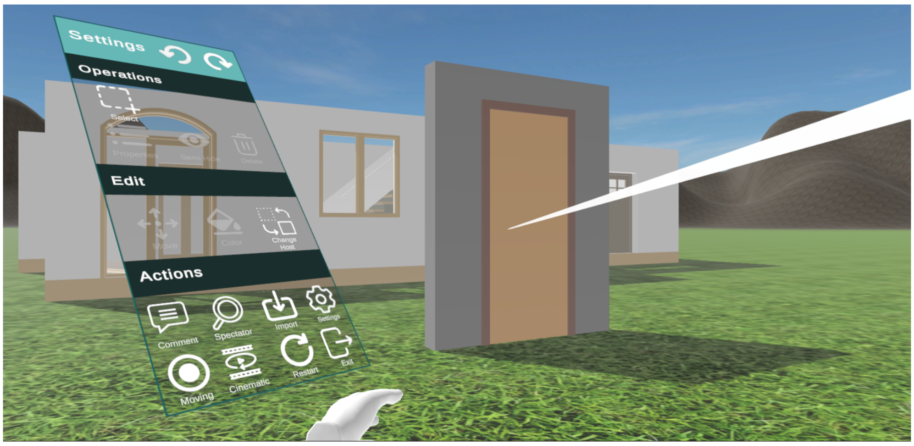
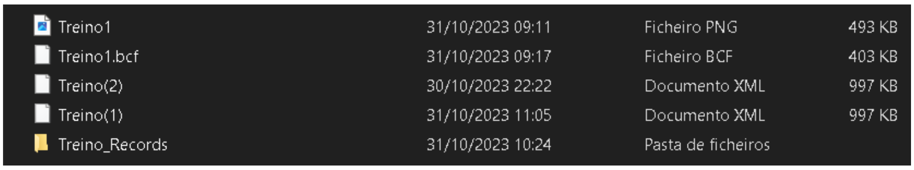


Figure 4.18: Undo functionality by reverting the deletion of an element (Figure 4.17b).

Tarefa-4	22/07/2023 22:09	Ficheiro IFC	2 378 KB
Tarefa-4(3)	07/08/2023 08:04	3D Object	5 175 KB
Tarefa-4(3).mtl	07/08/2023 08:04	Ficheiro MTL	3 KB
Tarefa-4(3)	07/08/2023 08:04	Ficheiro IFC	2 400 KB
Tarefa-4(2)	25/07/2023 13:31	3D Object	5 173 KB
Tarefa-4(2).mtl	25/07/2023 13:31	Ficheiro MTL	3 KB
Tarefa-4(2)	25/07/2023 13:31	Ficheiro IFC	2 399 KB
Tarefa-4(1)	25/07/2023 13:02	3D Object	5 160 KB
Tarefa-4(1).mtl	25/07/2023 13:02	Ficheiro MTL	3 KB
Tarefa-4(1)	25/07/2023 13:02	Ficheiro IFC	2 378 KB

Figure 4.19: IFC file version for the undo/redo functions and version control.

the IFC and the recording with the name of the time it was recorded, one example of this folder could be the Figures 4.20 and 4.21.



Treino1	31/10/2023 09:11	Ficheiro PNG	493 KB
Treino1.bcf	31/10/2023 09:17	Ficheiro BCF	403 KB
Treino(2)	30/10/2023 22:22	Documento XML	997 KB
Treino(1)	31/10/2023 11:05	Documento XML	997 KB
Treino_Records	31/10/2023 10:24	Pasta de ficheiros	

Figure 4.20: Recording folder of the IFC file.

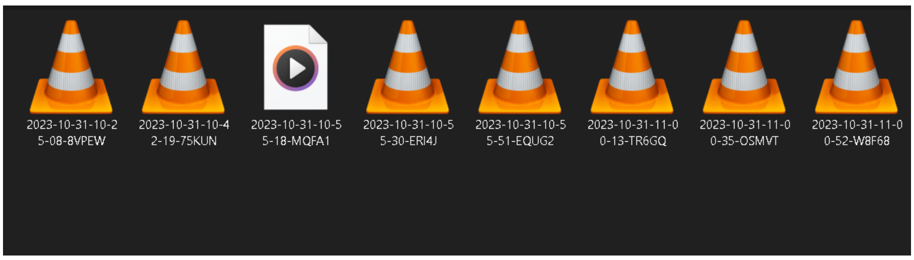


Figure 4.21: Videos from the recording feature.

4.4.13.1 First person

This functionality, as stated, is just recording the user's vision without the GUI and the hands of the controllers.

4.4.13.2 Cinematic

This functionality is more sophisticated because it allows to make a video around the model as if it were an upside-down tornado. Based on the settings given Figure 4.22a, the camera follows around the bottom of the model and rises to the extreme point, tapering towards the centre of the model (Figure 4.22b), taking into account only the visible elements (it is possible to make the second floor invisible, for example, and not appear in the video, only the first floor appearing)

(a) Cinematic recording options.

(b) Cinematic recording.

Figure 4.22: Cinematic recording functionality.

4.4.14 Other functionalities

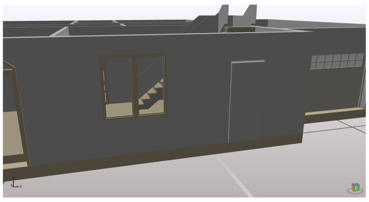
Other effort mentions were the God mode functionality, that in the computer version it worked as a a spectator, by making possible to pass trough walls for example, but in the VR version this functionality acted as a if it was like a jet pack. Furthermore, about changing the dimensions of an element, the ways of representing geometry in IFC schemas, are in the form of vertex mapping, or face mapping where it contains the vertices, modeling these is not easy in IFC schema, and just as difficult in Unity's mesh. So the potential for representing geometry in the form of IFC schema CSG primitives were studied, as these are possible to change (e.g. Height, Diameter, Length, etc.). IFC schema CSG primitives can be:

- Block.
- Rectangular pyramid.
- Circular cone.
- Circular cylinder.
- Sphere.

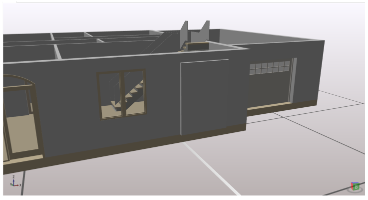
Operations between element geometry is possible:

- Union.
- Intersection.
- Difference.

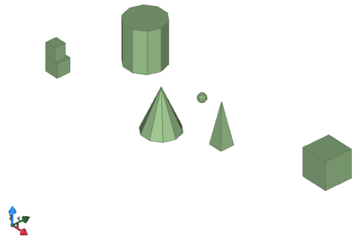
These primitives as well as the example of the Union between two cubes can be seen in Figure 4.23c. Then this principle of easily editable geometries was applied to the elements, as an example the Figure 4.23a, turned the geometry of the wall into another type of editable geometry, Solid Extruded Area, where it is possible to check the change of its geometry in the Figure 4.23b. These Figures were obtained outside the virtual environment, with the help of visualization software that supports IFC schema, such as usBIM.viewer+, and XBIM Explorer respectively.



(a) Changing the door geometry type, to an editable one.



(b) Change in the dimensions of the geometry.



(c) Creation of CSG primitive types, and a union of two blocks.

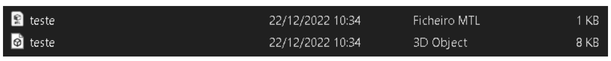
Figure 4.23: Other efforts.

4.5 Contributions to the Field

4.5.1 Revit API

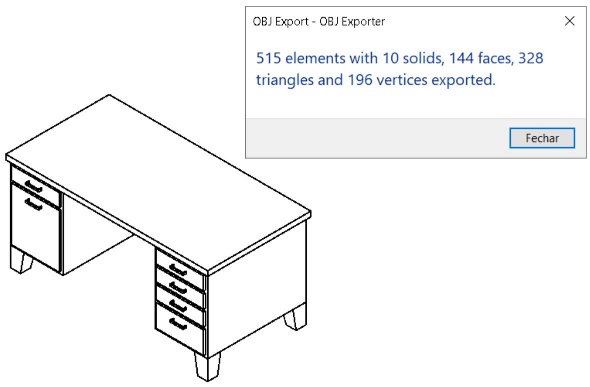
The API developed in Autodesk Revit, was created using the C Sharp language, and with the support of RevitApi dependencies and the Windows Forms system.

To run the API, the user must be in the 3D view to gather information, since Revit searches for information in the view in question. Before the export, a window for saving the file is presented, the file intended to be saved is the OBJ file, in which in this window, it prompts for the location where the file will be saved, as well as the file name. At the end of the export, the API presents the number of exported elements, solids, faces, triangles, and vertices (Figure 4.24b), as well as the creation of the OBJ file, and the MTL file that references the textures in the OBJ file (Figure 4.24a). This was the first approach that was later discarded.



teste	22/12/2022 10:34	Ficheiro MTL	1 KB
teste	22/12/2022 10:34	3D Object	8 KB

(a) Files resulting from the API export in Revit, more specifically the OBJ file, and its MTL file.



(b) Exporting the model, and displaying the end of export message in Revit.

Figure 4.24: Exportation with the plugin.

4.6 Conclusion

The main point of the chapter is the implementation and development of a VR application for BIM software using Revit and Unity as the chosen technology and game engine, respectively. The chapter discusses the advantages of VR in terms of immersive experience, training and teaching skills, and design and creativity. It also mentions the drawbacks of VR, such as the need for dedicated hardware and potential motion sickness. The section further explains the selected tools, including Revit software for BIM and Unity as the game engine and other software tools used in the project. The text also mentions the properties interface of the VR application, highlighting the importance of the properties and the features in the application.

Chapter 5

Evaluation

This chapter describes the system's implementation, testing, and assessment. First, it was required to run individual tests on key capabilities using the most frequent situations throughout the system's construction. Since the participants were students from various schools, prior knowledge exams were conducted before the test. Finally, students from the construction industry, many of whom are already employed or the end users, were tested. Several usability studies were conducted to evaluate the system, including the ITC-Sense of Presence Inventory (ITC-SOPI) questionnaires, the System Usability Scale (SUS), the NASA Task Load Index, a questionnaire on the project's influence on the construction sector, the Presence questionnaire, utilizing think aloud, and an examination of how the participant used the interface.

5.1 Procedure of the usability tests

In order to have a better VR experience, a beforehand work such as preparing the environment in the room (laboratory provided by the university) was needed.

In order not to collide with the physical environment when using the VR glasses, a feature of the glasses application was used, specifically Boundary, which is a built-in safety feature that lets you set up virtual walls that appear when you get too close to the edge of your play area, with one hand, the participant was virtually moved along the longitudinal axis using the analog joystick on one of the controllers. At the same time, the camera was operated using the other joystick on the other controller.

The participants received information on the technique before the sessions, provided informed consent to participate in the study, and completed a quick questionnaire regarding their age, gender, education level, and prior exposure to virtual reality and video games. They were once again told of the project's scope, objectives, and objectives just before the experiment. After receiving the brief information, they were assisted in donning the HMD. They adjusted them so they could enjoy it more comfortably and avoid contributing to a cause of cyber sickness.

The participants then engaged in free play in a basic simulation of the virtual environment in a large open area while hearing a simultaneous explanation of the possible actions they could carry out with the controllers and becoming accustomed to the camera movement with the HMD in conjunction with the joystick. After some getting accustomed, training was started to provide participants with a basic understanding of the controls, how to navigate, and how to complete some little activities that would later be used to illustrate more complex concepts.

This training served as the foundation for the participants' exploration of the various mobility options, including teleportation and more natural walking motions. The concept of how to interact with and use the game's menu and manually or automatically choose one or more options out of a range.

With the help of the Think Aloud Method that is used in cognitive psychology where people talk out their thoughts while they work on a problem, and it is frequently employed in study to learn more about how people solve problems and make decisions [92], the participants were given instructions (present in the Appendix I) to import the IFC associated with each activity. To evaluate different navigation or exploration situations, the initial step was to import the IFC file for task one, which required the participant to go to the top level before proceeding to a particular chamber on the lower floor.

The second challenge required us to locate a specific element in the model, see its many attributes, alter one, and then observe the automatic change in the model.

After the import in question, the participants were instructed to locate some specific walls readily apparent by the various materials on the walls, notably with varied colors, to put an editing scenario into effect on the model. To test some of the potential features on one wall, they were instructed to erase one wall, move another, and move a door within the third wall on these three walls.

The participants were instructed to import an IFC that more explicitly referred to a door and set it on a wall in the primary IFC model to import an IFC model into another IFC model or to insert a secondary IFC into a main IFC file.

Finally, after loading the final IFC file, the participants were instructed to create a cinematic film of the model's first floor, leaving the second story out of the frame.

The HMD was removed, and the participants were asked to briefly describe their experiences and express their preferences for how they would like to experience each activity. When asked to complete the post-questionnaire, they were instructed to be honest and to clarify any items they didn't understand or for which they had any concerns.

Table 5.1: Usability tasks summary.

Usability tests	
Pre-Questionnaire	Participant info
Presentation	Introduction to the subject Goals, projects, and steps
Training	Free training Planned training
Tasks	1- Movement/Exploration 2- Properties 3- Edition 4- Importation 5- Video making
Post-Questionnaire	SUS, Presence questionnaire, and another questionnaires
Final feedback	Participant feedback, and acknowledgements

5.2 Participants

The participants in the test mentioned in the preceding item are introduced in this subsection.

The participants were separated into various distinct days and times and tested one by one without being shown the prior ones.

In conducting the usability test, there were 15 participants, wich exhibited a diverse age range, with an average age of approximately 21 years old and a standard deviation of 4 and half years, highlighting a moderately varied age distribution. Geographically, our participants were drawn from the Universidade da Madeira. Notably, approximately 13.3 percent of the participants identified as working students, indicating a cohort balancing both academic and professional responsibilities, and the other 86.7 percent were full-time students. Participants come from different educational backgrounds, such as, Technology, Management, Humanities, Health, and Construction engineering, reflecting a mix of students some of them with exposure to the construction industry. In education 20 percent have a degree, approximately 13.3 percent have graduated, and the rest are post High Schooled. Concerning computer experience related to education, a significant 86.7 percent of participants possessed intermediate exposure to computer systems, showcasing a substantial level of familiarity within the tests, and the rest around 13.3 percent as basic computer experience. Also, 40 percent of our participants had previous experience with VR technology, signifying a substantial proportion of individuals well-acquainted with immersive virtual environments. In terms of knowledge about VR, a significant 73.3 percent approximately of participants demonstrated a basic understanding of VR concepts, and 13.3 percent as none, indicating a relatively under level of familiarity with the technology. Additionally, we observed that 20 percent of the participants never had a habitual engagement with video games played video games, and 6.67 percent approximately occasionally play them, suggesting that more than half of the participants established comfort and familiarity with interactive digital experiences.

An overview of this information can be seen in detail in the Appendix B graphs:

- Graph B.1 refers to the age of each participant.
- Graph B.2 indicates the participants' different fields of study.
- Graph B.4 depicts the education the participants have.
- Graph B.3 shows the occupation of the participants.
- Graph B.5 explains the different levels of experience with computers.
- Graph B.6 represents whether the participant has ever used VR.
- Graph B.7 tries to show the participant's knowledge of VR.
- Graph B.8 explains how often participants play video games

5.3 Evaluation of the system

5.3.1 Quality evaluation

This subsection will present all the qualitative evaluations from the usability tests. From the usability tests carried out, this evaluation was made considering the different characteristics of the tests, such as area of study, practice with VR or video games, and previous knowledge/experience with games or systems used with analogue controls.

One of the points that stood out in the evaluations was the fact that some of the users who already had more experience with games, and even with analogue controls, were able to perform the tasks more quickly, treating the test as a race to see if they could finish as soon as possible. In contrast, the other users had more difficulty using the analogue controls and interfaces. But in the end, even a user who had never played video games managed to complete all the tasks and even found the system fun and immersive.

There were some difficulties during the tests, as can be seen in Figure 5.1, where they included the fact that some people had trouble with the properties task, in terms of locating where the property value was found, what was being typed by the virtual keyboard, and where they could change the value.

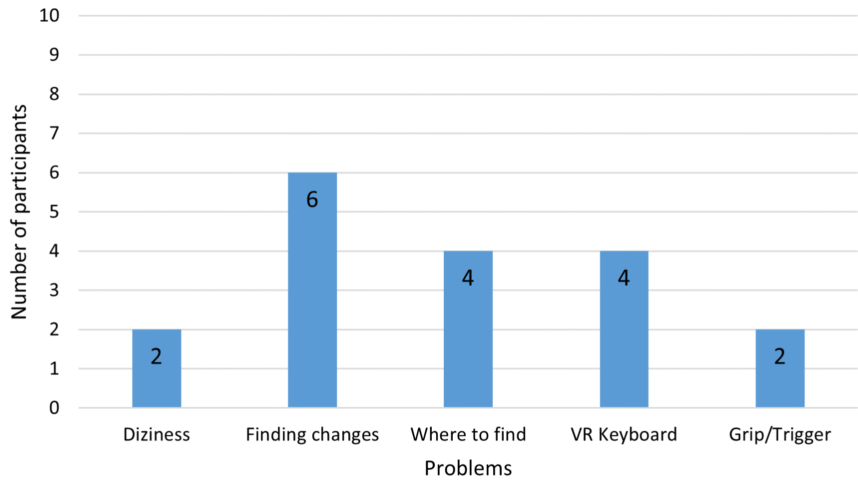


Figure 5.1: Participants difficulties in the evaluation.

Except for two users, participants typically reported having little motion sickness. These systems' two primary properties may be the cause of this variation. First, the delay between the movement of the head and the import of the IFC may cause nausea. Motion sickness is brought on by discrepancies between visual and vestibular stimulation, even though this was not examined in the research. The relationship between vestibular stimulation and the presence of motion. The reduced sense of presence and suppression of motion sickness are related to how well the glasses fit the wearer's face.

5.3.2 Quantitative evaluation

In this section, all quantitative evaluations resulting from usability tests will be presented. The results from the questionnaires as well as their conclusion.

The average duration of each activity are shown in Table 5.2. Each usability test took an average of 31 to 36 minutes to complete.

Table 5.2: Usability tasks time duration results.

Usability tests	
Steps	Mean Duration (m:s)
Pre-Questionnaire	2:00
Presentation	3:10
Training	4:10
Tasks	8:31-12:04
Post-Questionnaire	9:00
Final feedback	4:00

5.3.2.1 SUS questionnaire

It is possible to calculate each participant's point total, which ranges from 0 to 100, using their responses to each question from the SUS questionnaire Appendix G. This is done using the formula shown below:

```
((Q1-1)+(5-Q2)+(Q3-1)+(5-Q4)+(Q5-1)+(5-Q6)+(Q7-1)+(5-Q8)+(Q9-1)+(5-Q10))×2,5     (1)
```

The results of the SUS questionnaire for each participant, calculated using the previously presented formula, are shown in Table 5.2.

By looking at Table 5.2, the highest and lowest scores on the survey, respectively, were 42.5 and 92.5 points, giving rise to a mean score of 72.5. A product is deemed acceptable when its score ranges between 70 and 100 points [12] [13]. The product's average score is over 70 points, making it "Good" in the adjectival classifications.

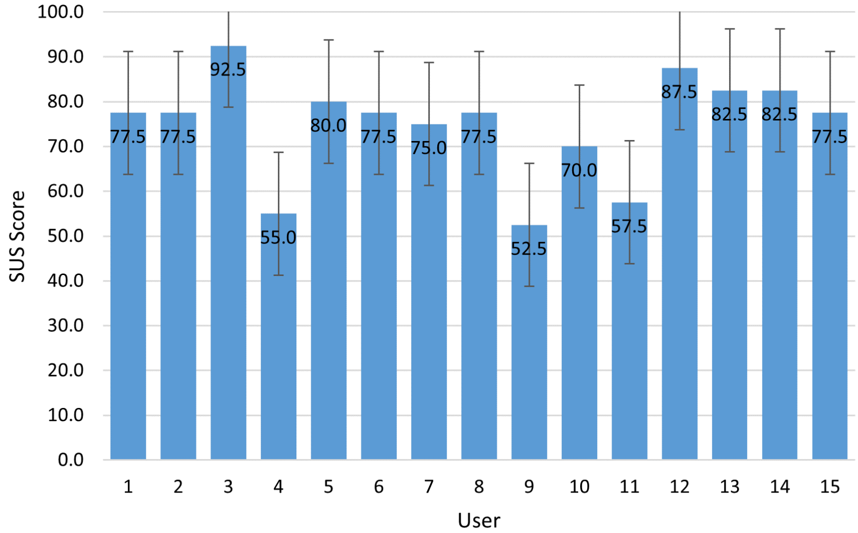


Figure 5.2: Score of the results of the System Usability Scale.

5.3.2.2 ITC-SOPI questionnaire

A popular survey used to evaluate the sensation of presence people feel is called the ITC-sensation of Presence Inventory (ITC-SOPI). It includes several questions that assess many facets of spatial presence, engagement, naturalness, and negative effects. The checklist aids in understanding and quantifying the subjective sense of being "present" in a virtual or mediated environment.

Appendix D shows the form given to users, by agreeing or disagree the statements using a 5-point scale, and Figure D.1 in the same shows each user's result for each task, and the ITC-SOPI mean score can be seen in the following Figure 5.3.

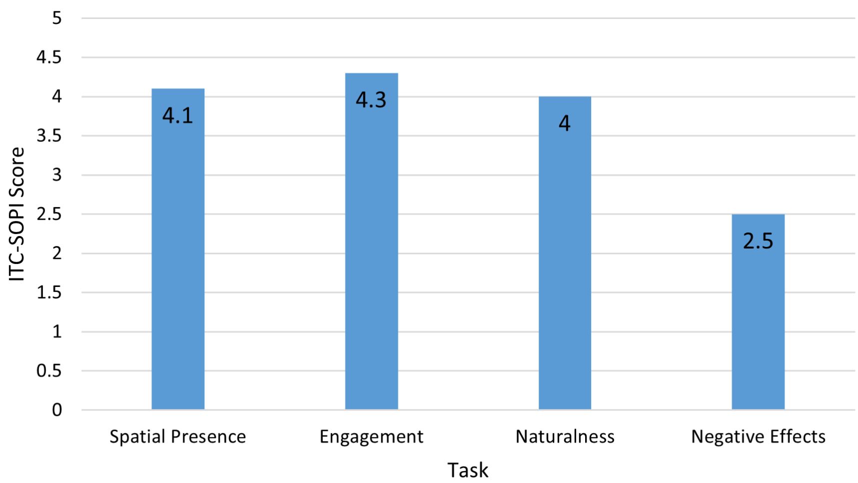


Figure 5.3: ITC-SOPI mean score.

Based on the Spatial Presence mean score of 4.1, participants felt like they were in the simulated or virtual environment. This suggests that the project's technology or setting successfully transported participants into the virtual world and gave them a sense of immersion. Based on the mean Engagement score of 4.3, participants were successfully engaged in the project. This suggests that the participants were captivated by the initiative and found it amusing. Based on the 4.0 mean of Naturalness, it can be inferred that the participants found the virtual environment or experience to be reasonably realistic and natural. This suggests that the technology or simulation used in your project accurately mirrored real-life situations, which can be viewed as a positive conclusion. With Negative Effects mean of 2.5, participants generally reported relatively low adverse effects from the ITC-SOPI test. This is encouraging since it suggests no notable adverse reactions or uncomfortable experiences from the technology or expertise used in the project.

According to the ITC-SOPI test's mean scores for spatial presence, engagement, naturalness, and adverse effects, the project successfully gave participants an immersive, engaging, and natural experience while limiting negative consequences. These results show that the project met its objectives and was positively received by the participants.

5.3.2.3 Presence questionnaire

The Presence questionnaire includes questions that measure various dimensions of presence, such as the Quality of the interface Appendix F.4, Realism Appendix F.1, the Possibility to examine the environment Appendix F.3, and the Possibility to act within it Appendix F.2. These dimensions help to understand the effectiveness and impact of the software on participants' perception of presence and their ability to interact with the environment.

This questionnaire was divided into two sections: the experienced environment and the haptic (sense of touch). These sections can be seen in the questionnaire in the Appendix E and F. Figure 5.4 shows the average value for each dimension, showing that the participants prefered the possibility to examine and explore the environment.

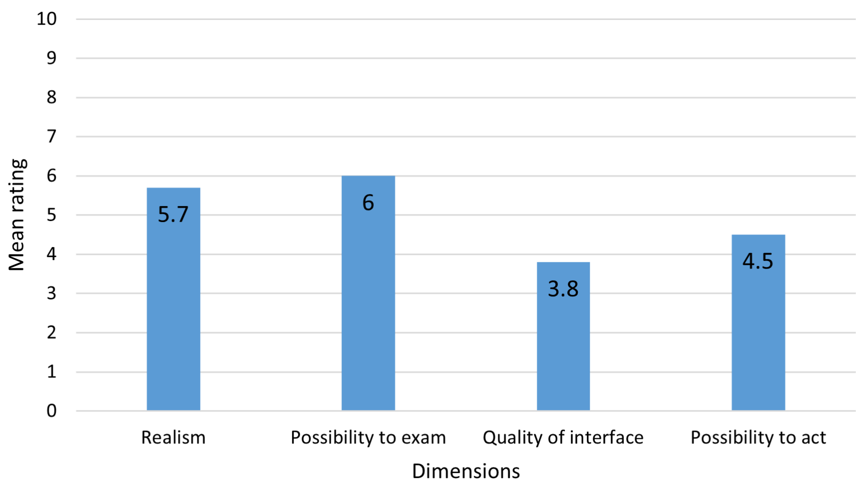


Figure 5.4: Mean of the different Presence Questionnaire dimensions.

5.3.2.4 NASA Task Load Index

From a set of ratings across six dimensions: mental demand, physical demand, temporal demand, effort, performance, and frustration level. The NASA Task Load Index, provides a way to assess the overall workload experienced by the users while performing a task.

Its questions are presented from a website [65] that gives and calculates the values all online. The average score can be seen in Figure 5.5, and in the Table 5.3, the rank, the scale, and its due score is visible, with the system demanding more mental >performance>effort>physical> frustration>temporal [Table 5.3.

This score was averaged to give an average effort of 29.4, which, according to the tabulated values, is labelled with the Low Workload category. The average mental demand score for the project were 133.7, indicating a substantial cognitive burden for the participants. This suggests that a significant amount of mental effort and focus were needed to complete the assignment. The performance had a mean score of 112.3, suggesting that participants thought they did well overall. This is a good result since participants believed they accomplished their objectives well despite the mental strain. The average effort score of 87.0

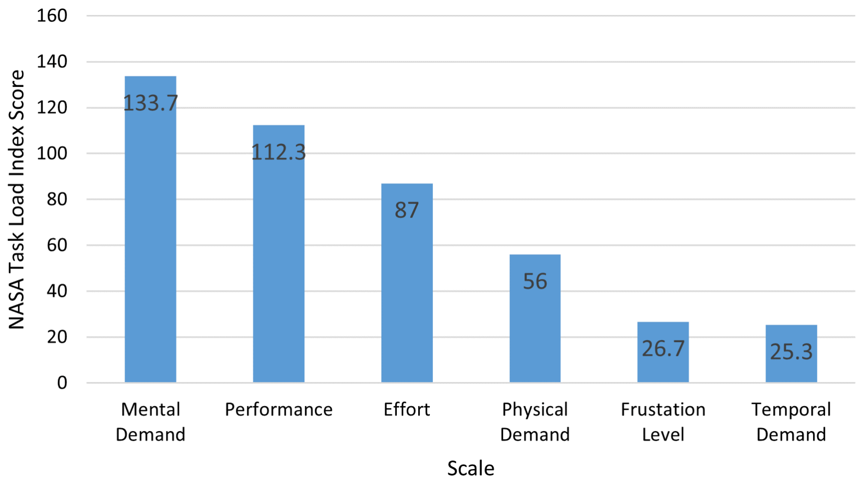


Figure 5.5: Nasa Task Load Index mean score.

Table 5.3: NASA Task Load Index ranking

Rank	Scale	Score	
	1	Mental Demand	133.7
	2	Performance	112.3
	3	Effort	87.0
	4	Physical Demand	56.0
	5	Frustration Level	26.7
	6	Temporal Demand	25.3

indicates that participants worked hard to finish the exercise. This is consistent with the high Mental Demand score, which shows that mental and physical effort was needed to complete the assignment. The comparatively low Physical Demand mean score of 56.0 suggests that participants did not generally perceive the job as physically demanding. This implies that the task was less physically demanding and more cognitively challenging. The comparatively low mean score of 26.7 for Frustration Level suggests that participants did not, on average, feel a great deal of frustration while completing the activity. Low degrees of frustration indicate a more manageable and user-friendly activity. With a Temporal Demand mean score of 25.3, participants only thought the task required a little time, as indicated by the low mean score. From this, the task was effective and didn't take too long to finish.

In conclusion, the NASA-TLX evaluation of the project indicates that the activity was intellectually demanding and required a significant amount of effort from participants based on the mean scores for Mental Demand, Performance, Effort, Physical Demand, Frustration Level, and Temporal Demand. They were satisfied, though, and they were generally happy with how they performed. There wasn't any physical strain or excessive time required for the task.

5.4 Conclusions

In general, positive results were obtained in the qualitative and quantitative evaluations. It was crucial to recognize whether there were any aspects or functionalities that needed to be changed or added to have a system that was more comprehensive and comprehensive from a functional and construction standpoint, taking into account the experience that some participants had in the area. Throughout this evaluation, usability tests did not uncover any operational or technical errors in general in the system.

Chapter 6

Discussion and Conclusions

A thorough investigation into the integration of VR and BIM technologies in this dissertation was conducted, concentrating on communication techniques, problem identification, bidirectional information flows, Unity3D implementation, and Oculus Rift HMD use and testing. All the development and conclusions show that all objectives were accomplished, giving the AECO sector insightful knowledge despite this project being a demonstration.

First off, there was research and effort on the process of turning BIM models into VR models. The accomplished creation of two-way information flows between these two vital technologies has demonstrated the possibilities for improved decision-making, visualization, and cooperation in the AECO industry. This accomplishment moves us closer to a smooth transition from the planning and design stages to the building and operating stages, ultimately improving project efficiency.

Second, a crucial contribution of this research has been the identification of issues and efficient communication techniques. The AECO sector frequently needs help with cooperation and communication between many stakeholders. This project shows strategies or workarounds to tackle this issue. To show this, in the beginning there was no exchange of information about materials and elements and only geometric data, which led to the adoption of the IFC file, which served as the foundation for bidirectional communication between BIM and VR by filling the gaps that currently exist in the in the AECO sector, and used software by spliting it in three files that retained information regarding the information of the elements, geometry, and materials.

The third objective, implementing Unity3D and Oculus Rift S, allows BIM-to-VR technology to be used in real-world scenarios. Because of Unity3D's adaptability and the immersive experience offered by Oculus Rift, architects, engineers, and construction professionals have a viable platform for more productive interaction with 3D models and simulations. This was made by developing a BIM and VR approach and create conceptual and logical models for this information sharing. A computer version in a virtual environment was created to act as prototype for the VR version, with various capabilities that a end-user would find helpful or required being built into it. The features of the computer version were converted to VR, and this conversion proved quite tricky regarding features and interface because some things were possible or not, closing some doors to chances while opening others. The functionalities were improved after conversion to make them as strong as feasible for testing.

Moreover, using VR design in one or more AECO industry sectors is a successful real-world example of the technology's potential. VR's incorporation into construction planning, facilities management, and architectural design processes are a few examples of how this project, despite being a demonstration, could be used with future work. It could be used to innovate and streamline real-world tasks, in the fields of communication, design, data exchange, and even education.

For the testing portion, which took place over several days and involved 15 participants—all students with varying educational backgrounds, some of whom worked in the construction industry and others who were also workers in the field, making them the ideal target audience. The Oculus Rift was employed as an HMD during system testing and design, and tests conducted in combination with the system using it demonstrated that it had low levels of cybersickness. The tests were broken down into six sections: a preliminary test to gather demographic data, an overview of the system and how it fits into the AECO sector, a free training session, a strict training session that followed tasks that would have evaluated the system and the participant's behavior, a post-questionnaire to evaluate the system using usability models, and finally a more individualized final fee. From the results of the tests and the participants feedback, it confirms the practicality and ease of use of the created VR solutions, as well as confirm that industry professionals could successfully use BIM-to-VR technology.

The accomplishment of these objectives successfully shows how combining BIM and VR can revolutionize the AECO sector. This work opens the door to improved decision-making, cooperation, and communication, ultimately leading to more successful and efficient project outcomes. The testing users accepted the tested application, which is a positive sign that this technology can influence AECO practices in the future.

A last point to make is that this system has a lot of promise, and the outcomes of this research might serve as a solid foundation for future initiatives of a similar nature or use in other AECO-related applications.

6.1 Limitations and future work

Even though all objectives were met, there were certain challenges encountered as the project was being developed.

This system had several limitations, for example, the fact that it was not possible to create from scratch a converter from IFC schema to Unity, and vice versa, or even the creation of a plugin in Autodesk Revit or an external executable that would do the automatic importing, and real-time changes to the model. Even with the help of translating libraries from languages other than C Sharp that support the IFC schema, this was impossible because it meant giving up time to achieve the other proposed objectives. Another limitation would be the impossibility of editing the length and width of any element, as well as updating its fundamental quantities dynamically, in the change of dimensions because most elements contain a mesh composed of different types of geometric representation or vertex base, which makes their manipulation in IFC schema as well as in Unity not a straightforward or advised approach.

The solution's performance when loading huge IFC files has a significant constraint since the system freezes when loading IFC files, and the larger the IFC file, the longer it takes to open the first time.

In terms of future work, there are many directions of development that can be covered. One Direction would be the implementation of interaction with model elements, for example opening doors. Other directions would be from this project, to be other application of VR applications in the AECO industry, for example in terms of collaboration and design, by making, the inclusion of multiple users in real time, in the immersive environment, with voice-chat, and other many features to be different from other applications that already exist. Also for future work, the idea is to integrate the project result into AR or MR technology

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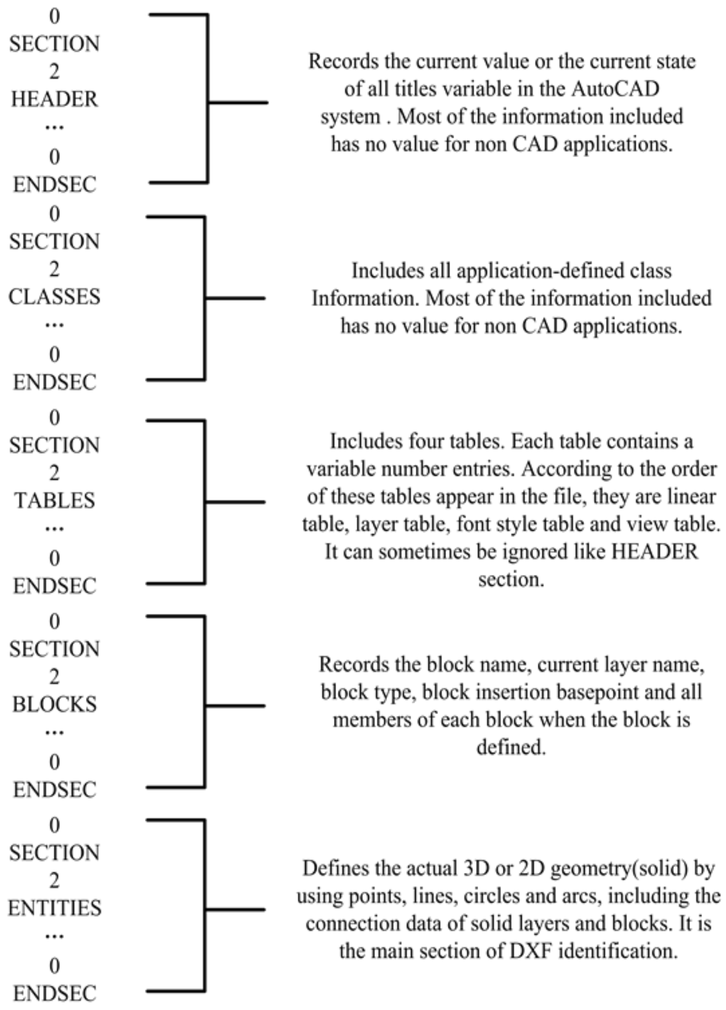
Appendices

Appendix A

DXF file structure



Appendix B

Participants demographic information

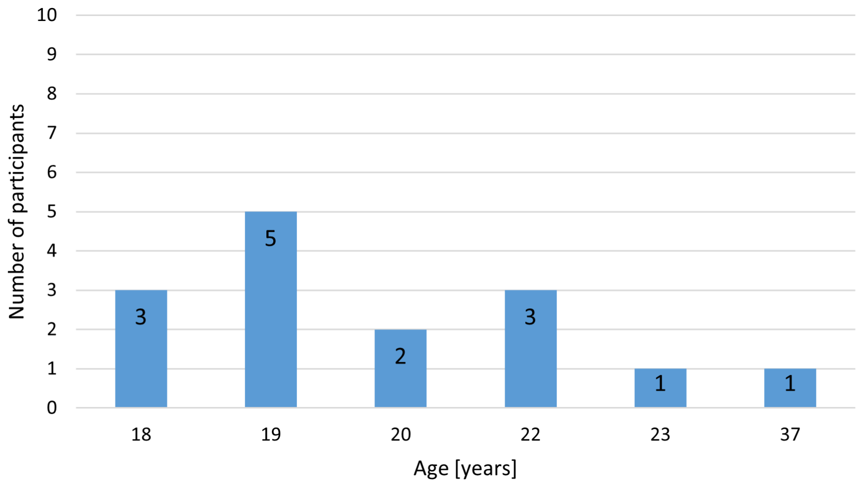


Figure B.1: Age from participants

.

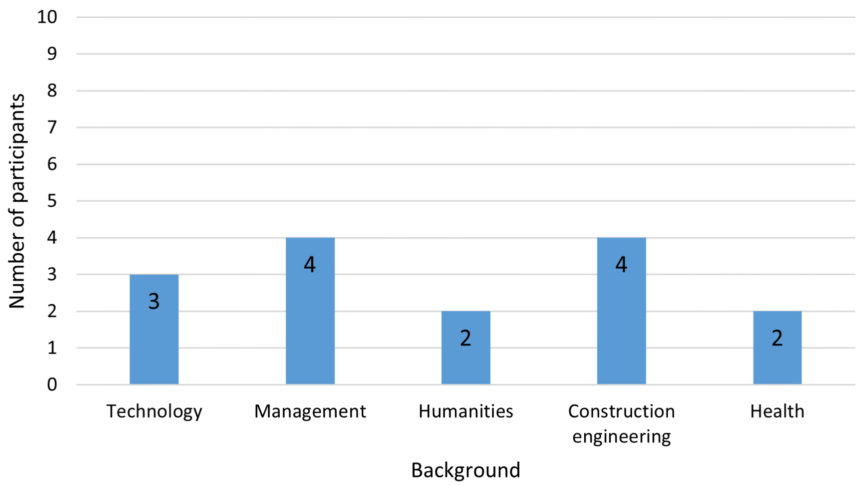


Figure B.2: User areas of education

.

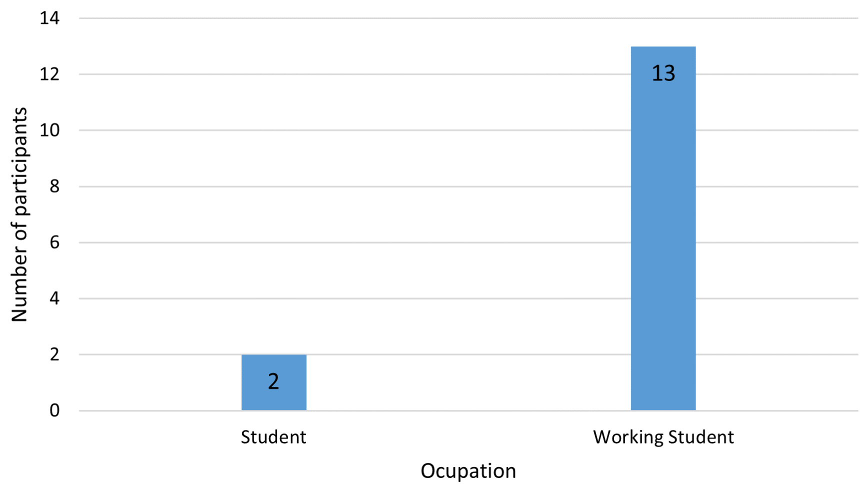


Figure B.3: Participants occupation

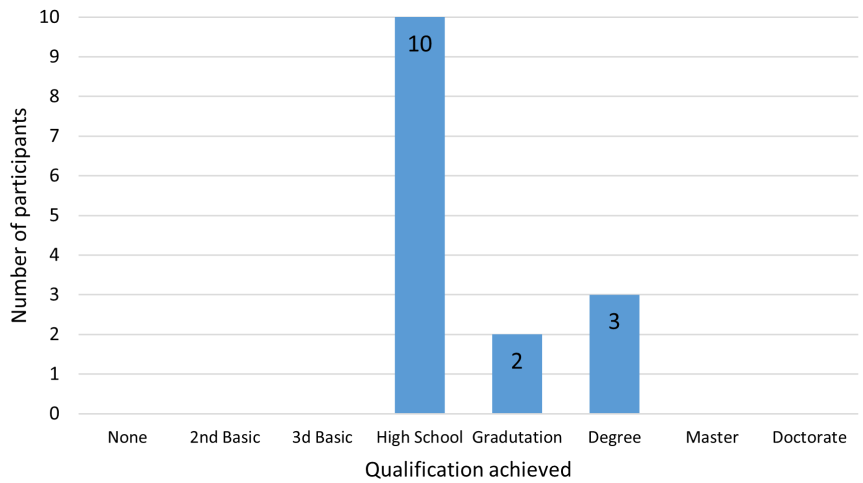


Figure B.4: Participants education

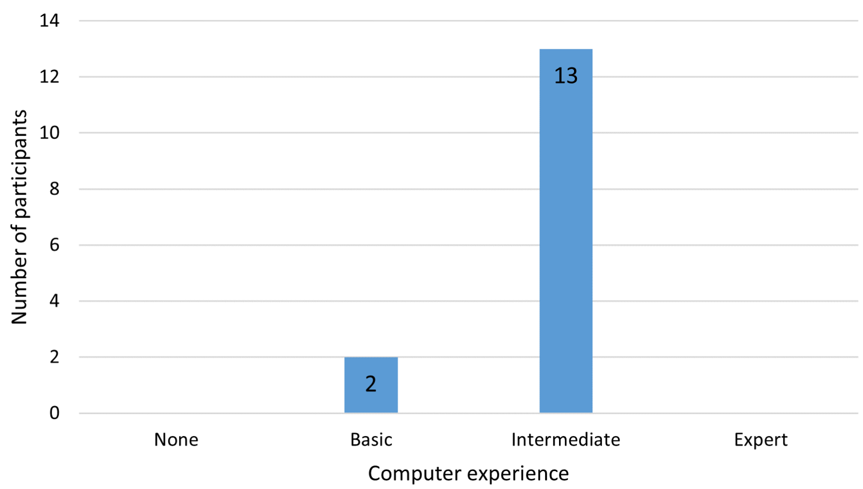


Figure B.5: Computer experience from participants

.

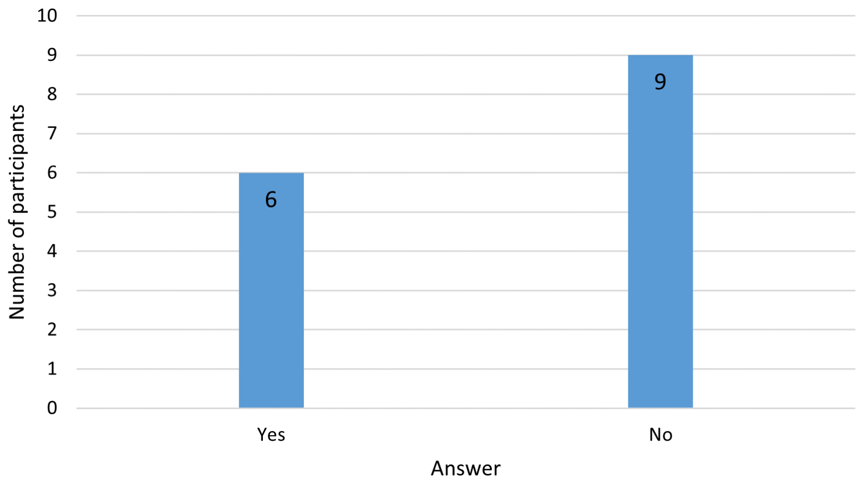


Figure B.6: Previous use of VR from participants
.

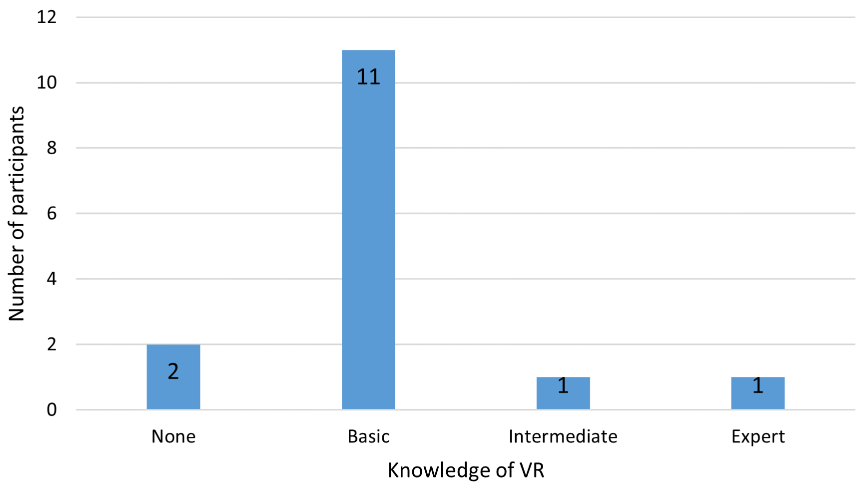


Figure B.7: VR knowledge from participants
.

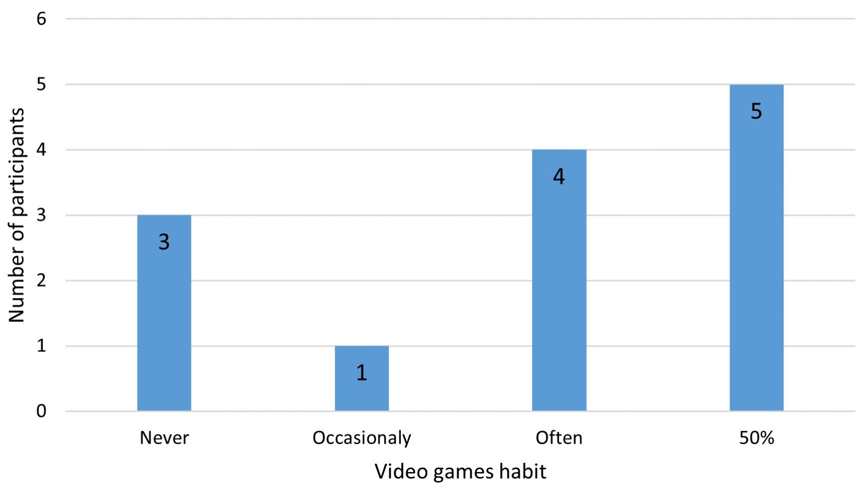
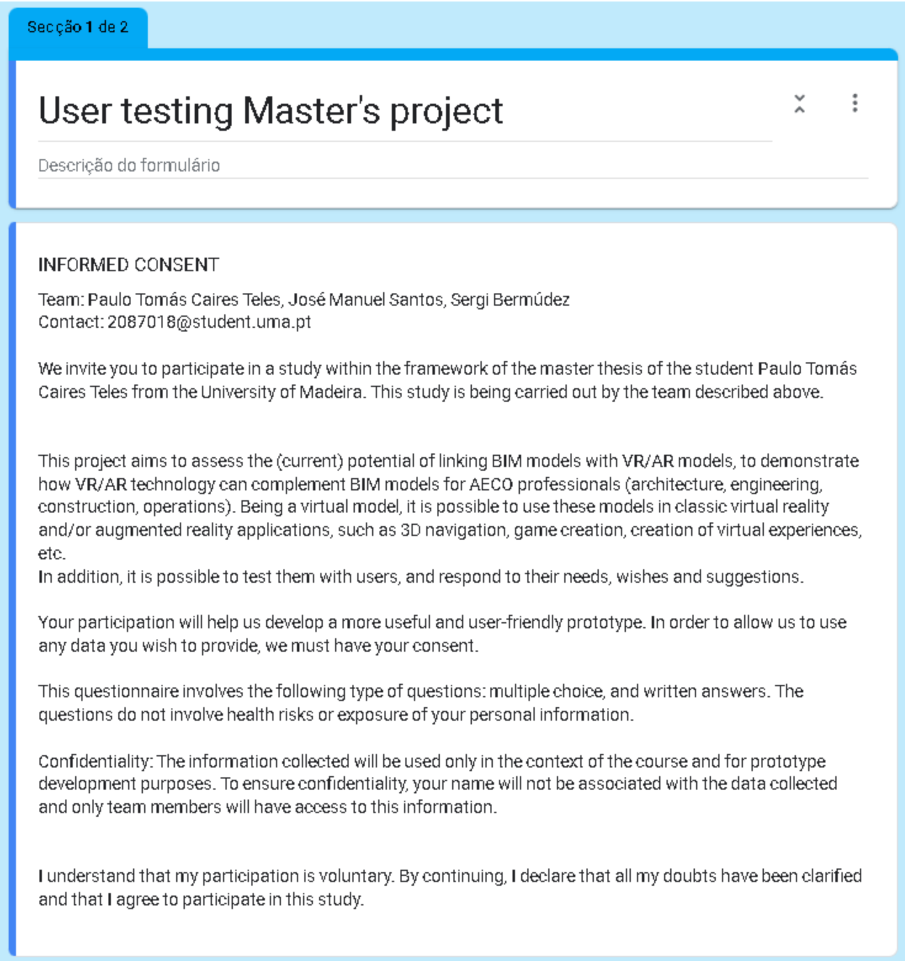


Figure B.8: Video games habit from participants
.

Appendix C

Pre Testing questionnaire



Secção 1 de 2

User testing Master's project

Descrição do formulário

INFORMED CONSENT

Team: Paulo Tomás Caires Teles, José Manuel Santos, Sergi Bermúdez
Contact: 2087018@student.uma.pt

We invite you to participate in a study within the framework of the master thesis of the student Paulo Tomás Caires Teles from the University of Madeira. This study is being carried out by the team described above.

This project aims to assess the (current) potential of linking BIM models with VR/AR models, to demonstrate how VR/AR technology can complement BIM models for AECO professionals (architecture, engineering, construction, operations). Being a virtual model, it is possible to use these models in classic virtual reality and/or augmented reality applications, such as 3D navigation, game creation, creation of virtual experiences, etc.
In addition, it is possible to test them with users, and respond to their needs, wishes and suggestions.

Your participation will help us develop a more useful and user-friendly prototype. In order to allow us to use any data you wish to provide, we must have your consent.

This questionnaire involves the following type of questions: multiple choice, and written answers. The questions do not involve health risks or exposure of your personal information.

Confidentiality: The information collected will be used only in the context of the course and for prototype development purposes. To ensure confidentiality, your name will not be associated with the data collected and only team members will have access to this information.

I understand that my participation is voluntary. By continuing, I declare that all my doubts have been clarified and that I agree to participate in this study.

Figure C.1: a)

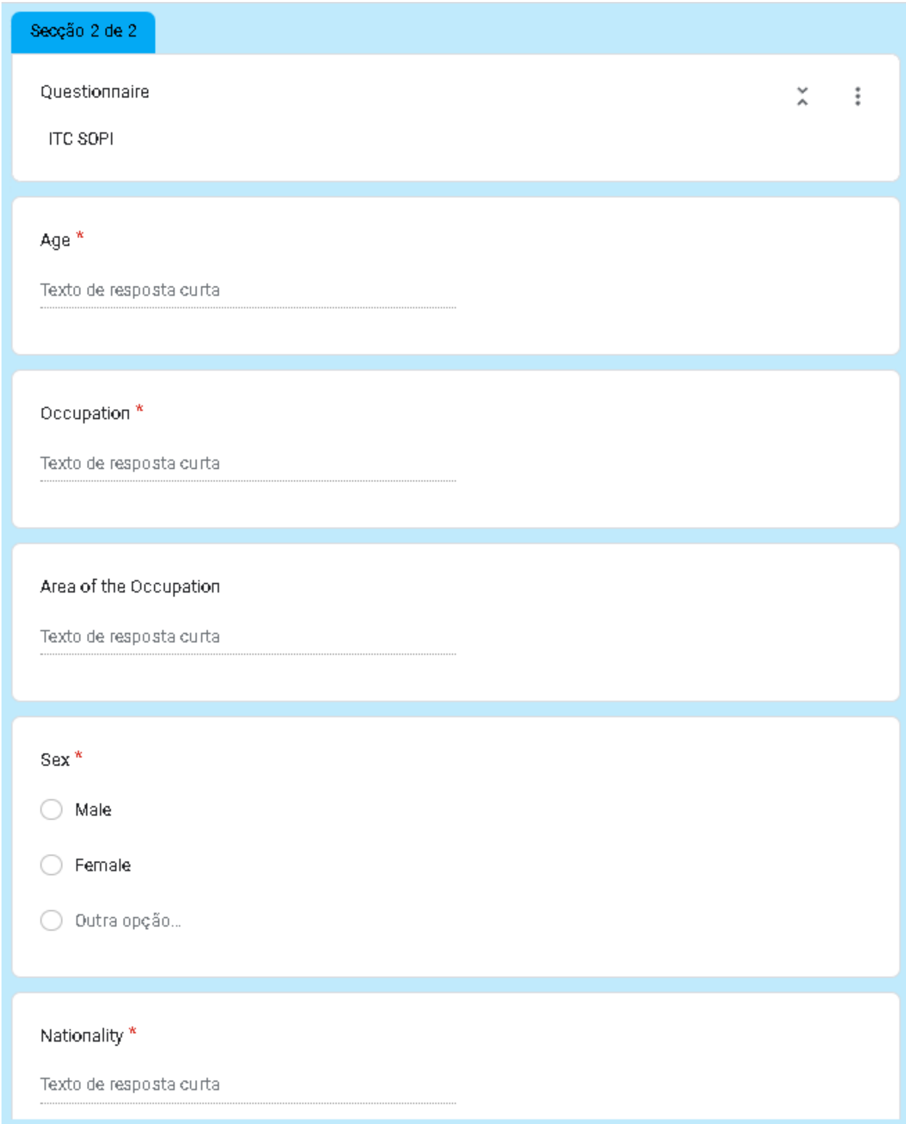

Secção 2 de 2
Questionnaire
ITC SOPI
Age *
Texto de resposta curta
Occupation *
Texto de resposta curta
Area of the Occupation
Texto de resposta curta
Sex *
Male
Female
Outra opção...
Nationality *
Texto de resposta curta

Figure C.2: b)

Rate your level of computer experience

- None
- Basic
- Intermediate
- Expert

How would you rate your knowledge of how 3D images are produced?

- None
- Basic
- Intermediate
- Expert

How would you rate your knowledge of virtual reality (i.e. how it works)?

- None
- Basic
- Intermediate
- Expert

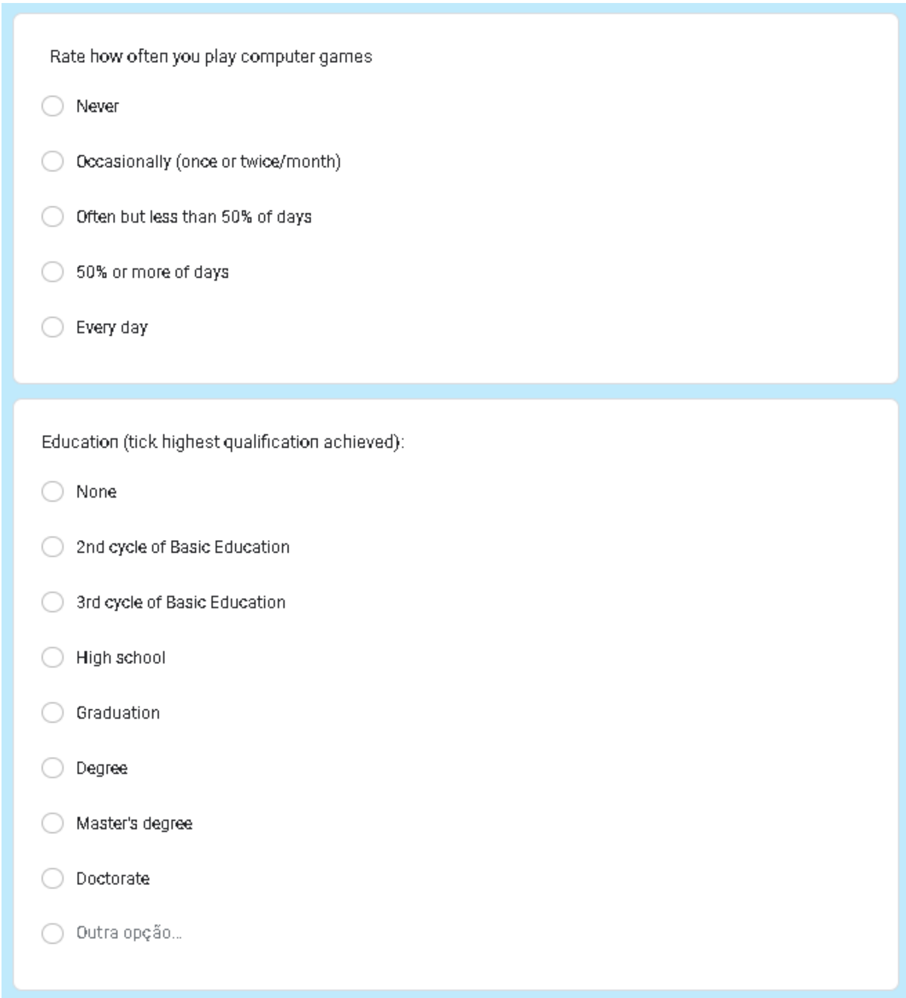
Have you viewed stereoscopic (3D) images using polarised glasses (e.g. IMAX 3D) before?

- Yes
- No

Have you used an experimental virtual reality system before (beyond a consumer computer/arcade game)?

- Yes
- No

Figure C.3: c)



Rate how often you play computer games

- Never
- Occasionally (once or twice/month)
- Often but less than 50% of days
- 50% or more of days
- Every day

Education (tick highest qualification achieved):

- None
- 2nd cycle of Basic Education
- 3rd cycle of Basic Education
- High school
- Graduation
- Degree
- Master's degree
- Doctorate
- Outra opção...

Figure C.4: d)

Appendix D

ITC-SOPI

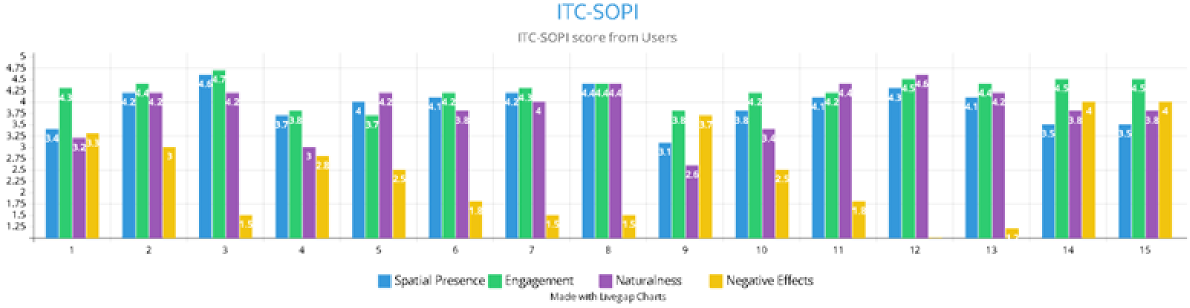
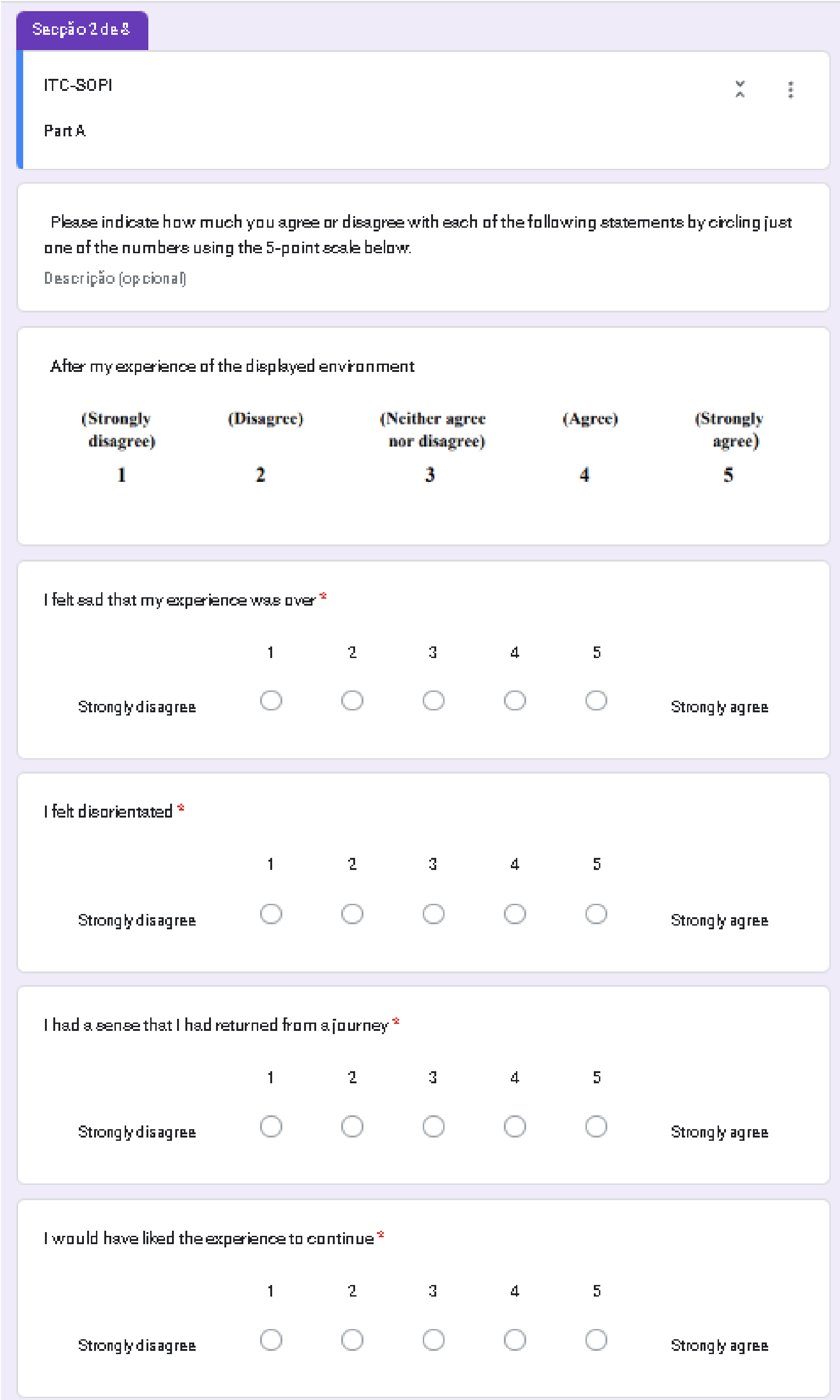


Figure D.1: ITC-SOPI score for every user.



Secção 2 de 8

ITC-SOPI

Part A

Please indicate how much you agree or disagree with each of the following statements by circling just one of the numbers using the 5-point scale below.

Descrição (opcional)

After my experience of the displayed environment

(Strongly disagree)	(Disagree)	(Neither agree nor disagree)	(Agree)	(Strongly agree)
1	**2**	**3**	**4**	**5**

I felt sad that my experience was over *

Strongly disagree 1 2 3 4 5 Strongly agree

I felt disorientated *

Strongly disagree 1 2 3 4 5 Strongly agree

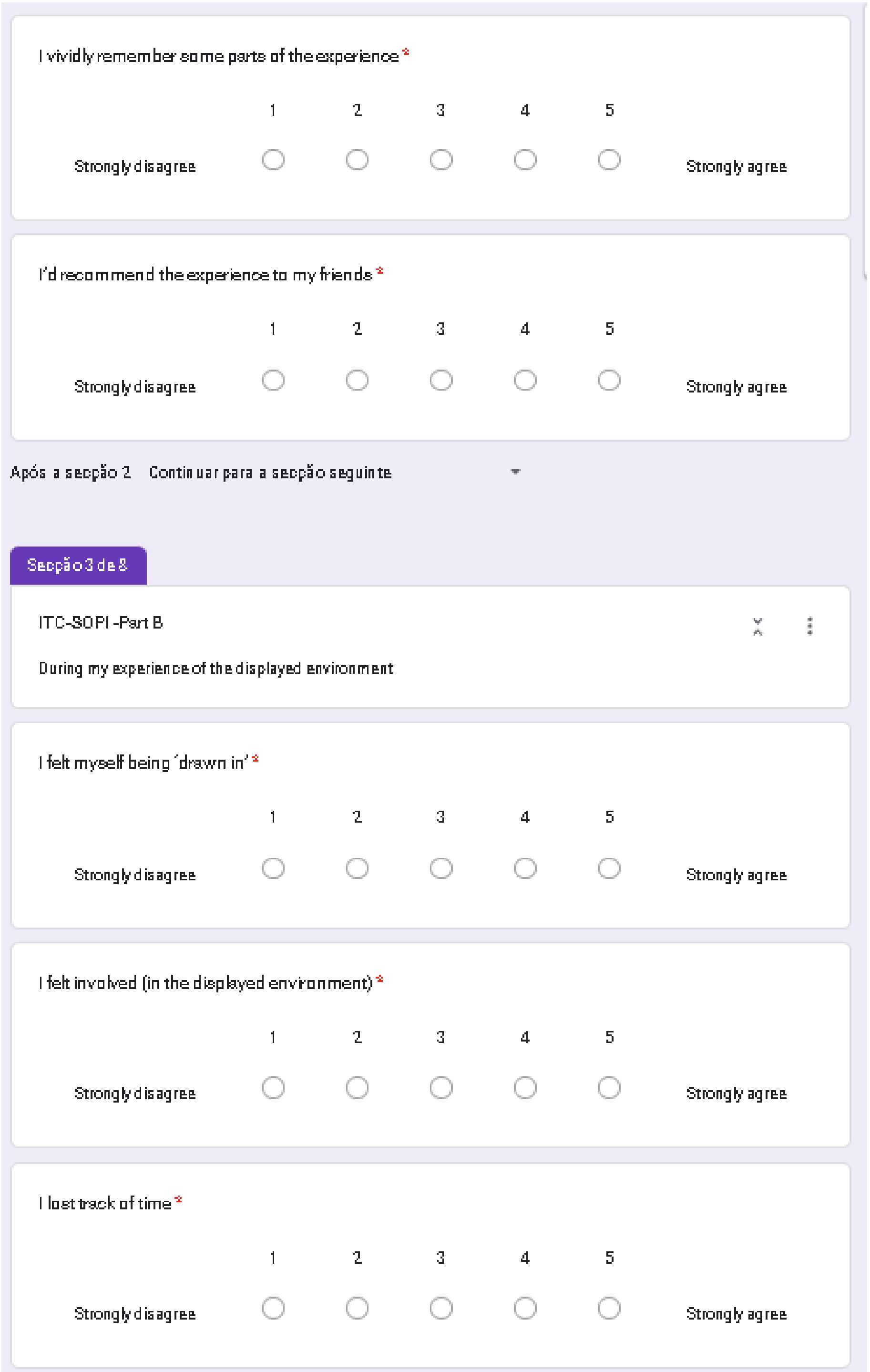
I had a sense that I had returned from a journey *

Strongly disagree 1 2 3 4 5 Strongly agree

I would have liked the experience to continue *

Strongly disagree 1 2 3 4 5 Strongly agree

Figure D.2: a)



I vividly remember some parts of the experience *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I'd recommend the experience to my friends *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Após a secção 2 Continuar para a secção seguinte

Secção 3 de 8

ITC-SOPI -Part B

During my experience of the displayed environment

I felt myself being ´drawn in´ *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

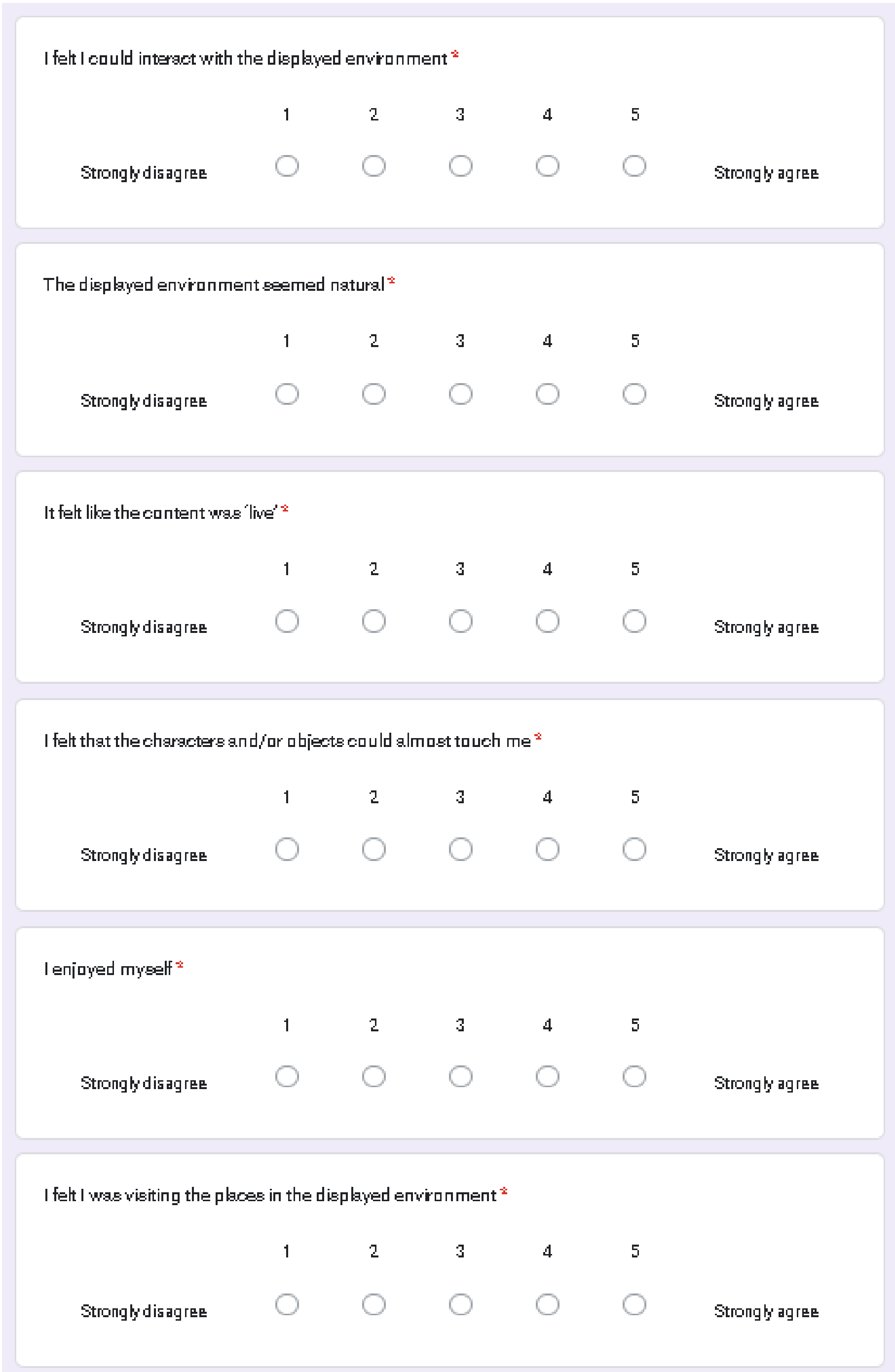
I felt involved (in the displayed environment) *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I lost track of time *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Figure D.3: b)



I felt I could interact with the displayed environment *

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

The displayed environment seemed natural *

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

It felt like the content was 'live' *

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

I felt that the characters and/or objects could almost touch me *

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

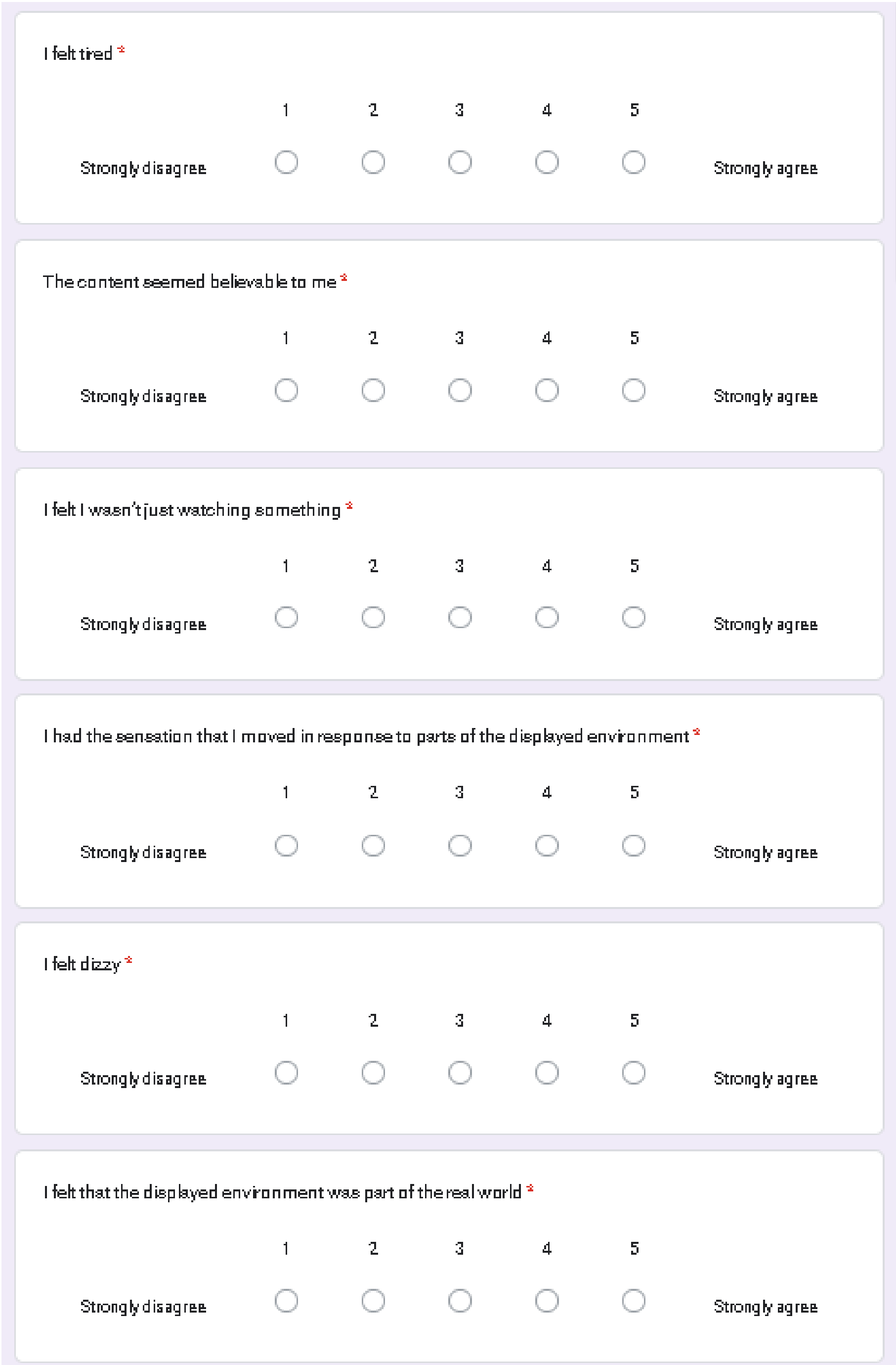
I enjoyed myself *

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

I felt I was visiting the places in the displayed environment *

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

Figure D.4: c)



I felt tired *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The content seemed believable to me *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt I wasn't just watching something *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had the sensation that I moved in response to parts of the displayed environment *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt dizzy *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt that the displayed environment was part of the real world *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Figure D.5: d)

My experience was intense *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I paid more attention to the displayed environment than I did to my own thoughts (e.g., personal preoccupations, daydreams etc.) *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had a sense of being in the scenes displayed *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt that I could move objects (in the displayed environment) *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

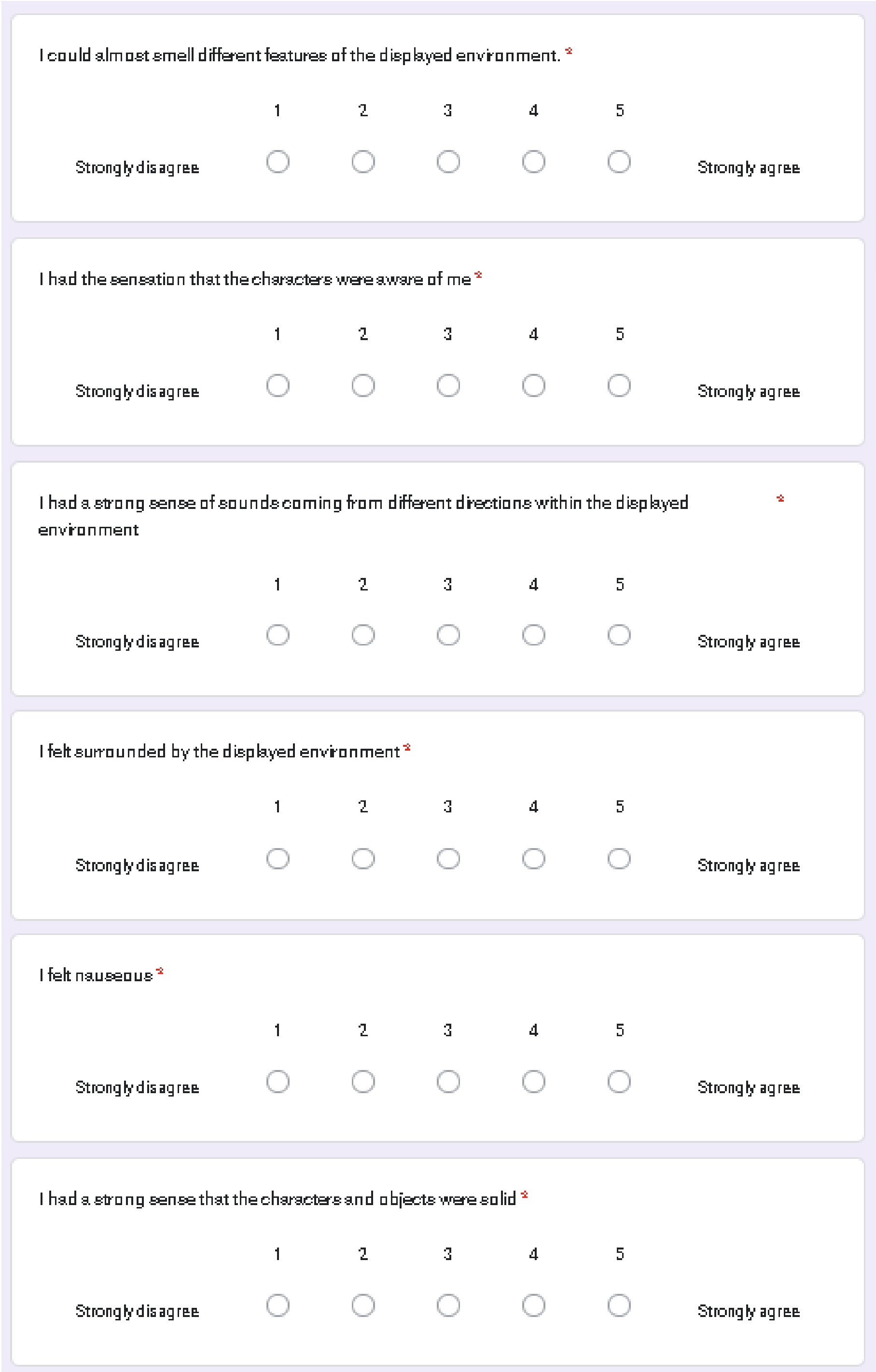
The scenes depicted could really occur in the real world. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt I had eyestrain *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Figure D.6: e)


I could almost smell different features of the displayed environment. *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had the sensation that the characters were aware of me *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had a strong sense of sounds coming from different directions within the displayed environment *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt surrounded by the displayed environment *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

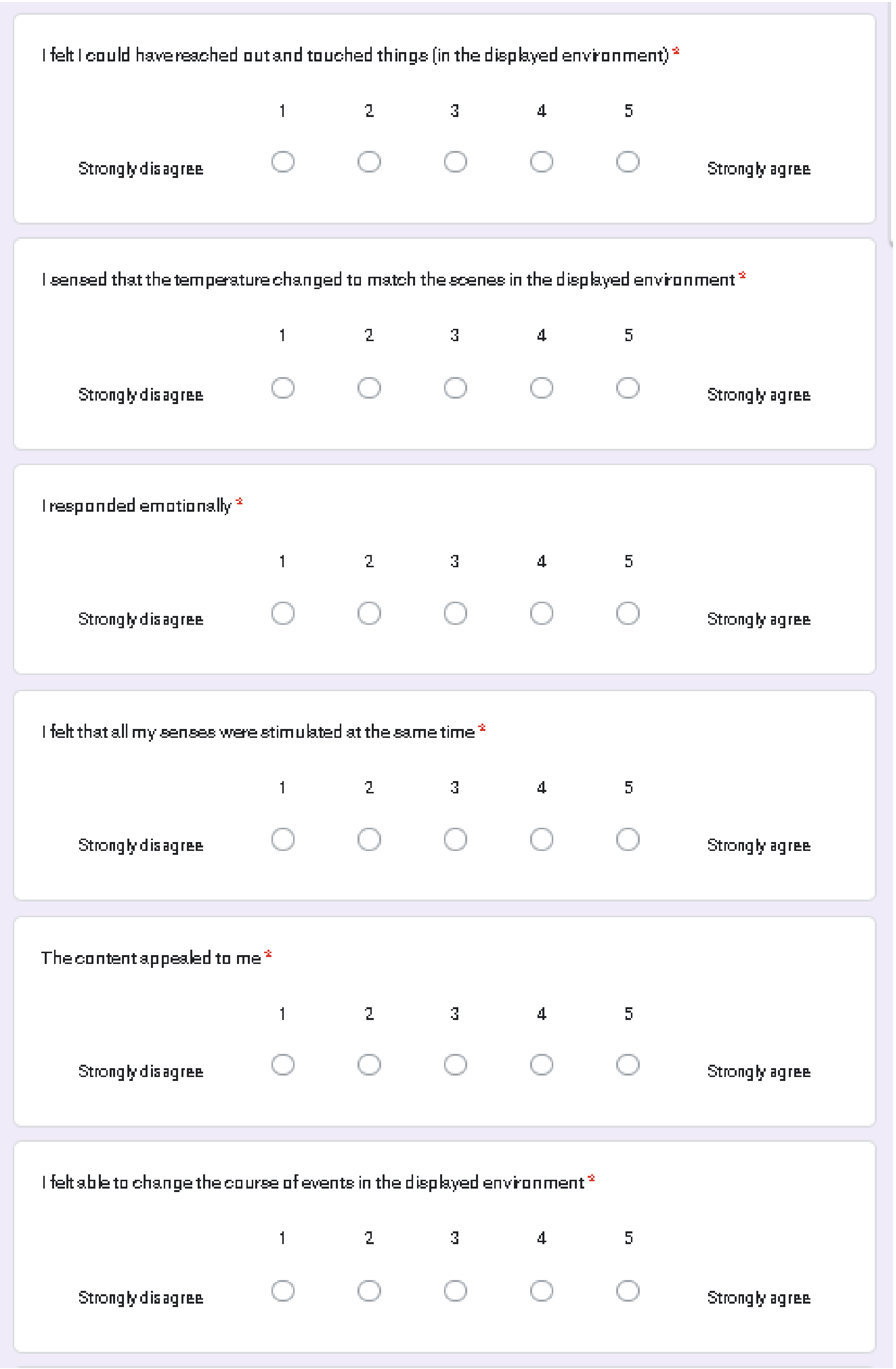
I felt nauseous *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I had a strong sense that the characters and objects were solid *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Figure D.7: f)



I felt I could have reached out and touched things (in the displayed environment) *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I sensed that the temperature changed to match the scenes in the displayed environment *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I responded emotionally *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt that all my senses were stimulated at the same time *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

The content appealed to me *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

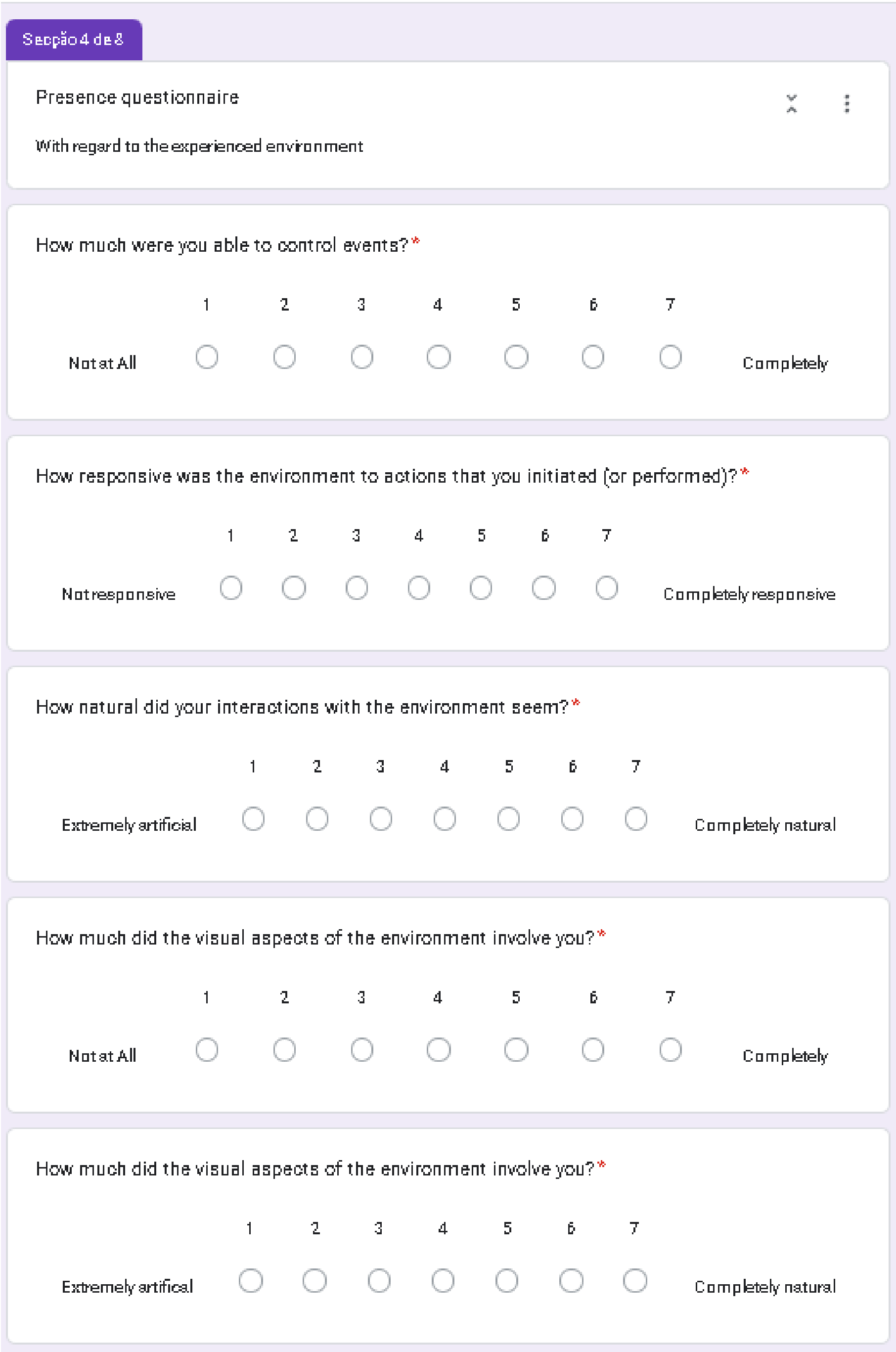
I felt able to change the course of events in the displayed environment *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Figure D.8: g)

Appendix E

Presence questionnaire



Seção 4 de 8

Presence questionnaire

With regard to the experienced environment

How much were you able to control events? *

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Completely

How responsive was the environment to actions that you initiated (or performed)? *

	1	2	3	4	5	6	7	
Not responsive	○	○	○	○	○	○	○	Completely responsive

How natural did your interactions with the environment seem? *

	1	2	3	4	5	6	7	
Extremely artificial	○	○	○	○	○	○	○	Completely natural

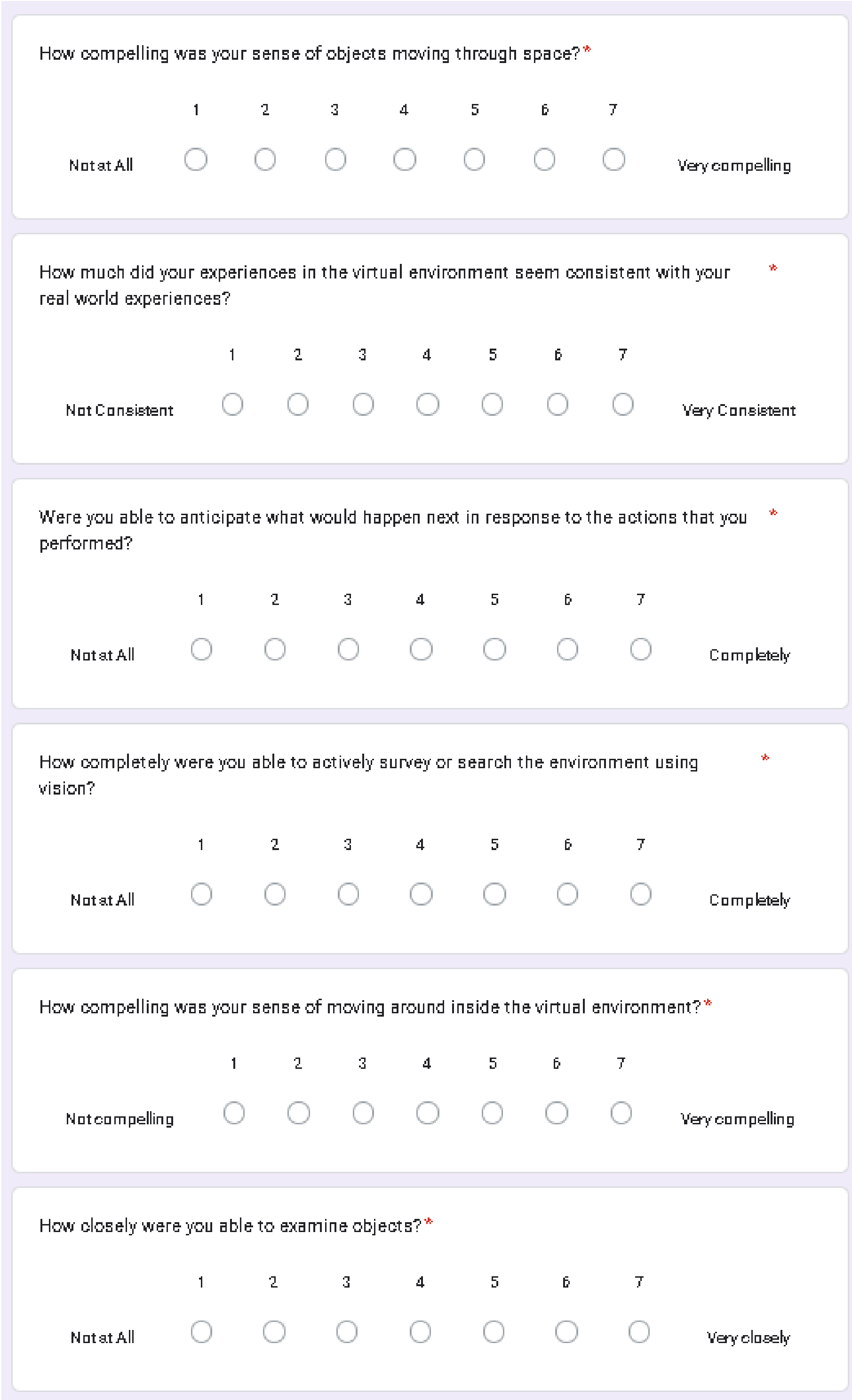
How much did the visual aspects of the environment involve you? *

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Completely

How much did the visual aspects of the environment involve you? *

	1	2	3	4	5	6	7	
Extremely artifical	○	○	○	○	○	○	○	Completely natural

Figure E.1: a)



How compelling was your sense of objects moving through space? *

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Very compelling

How much did your experiences in the virtual environment seem consistent with your real world experiences? *

	1	2	3	4	5	6	7	
Not Consistent	○	○	○	○	○	○	○	Very Consistent

Were you able to anticipate what would happen next in response to the actions that you performed? *

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Completely

How completely were you able to actively survey or search the environment using vision? *

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Completely

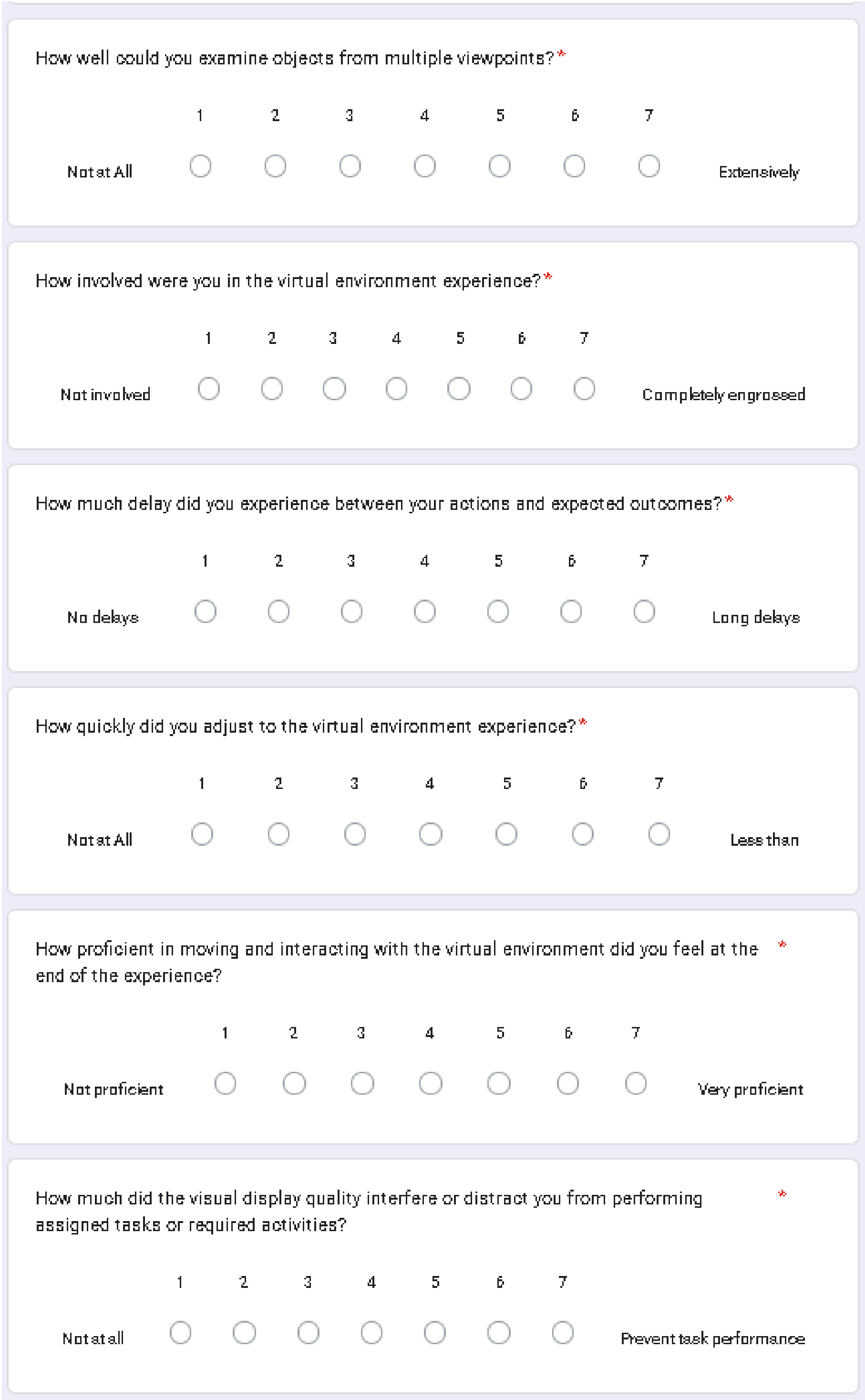
How compelling was your sense of moving around inside the virtual environment? *

	1	2	3	4	5	6	7	
Not compelling	○	○	○	○	○	○	○	Very compelling

How closely were you able to examine objects? *

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Very closely

Figure E.2: b)



How well could you examine objects from multiple viewpoints? *

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Extensively

How involved were you in the virtual environment experience? *

	1	2	3	4	5	6	7	
Not involved	○	○	○	○	○	○	○	Completely engrossed

How much delay did you experience between your actions and expected outcomes? *

	1	2	3	4	5	6	7	
No delays	○	○	○	○	○	○	○	Long delays

How quickly did you adjust to the virtual environment experience? *

	1	2	3	4	5	6	7	
Not at All	○	○	○	○	○	○	○	Less than

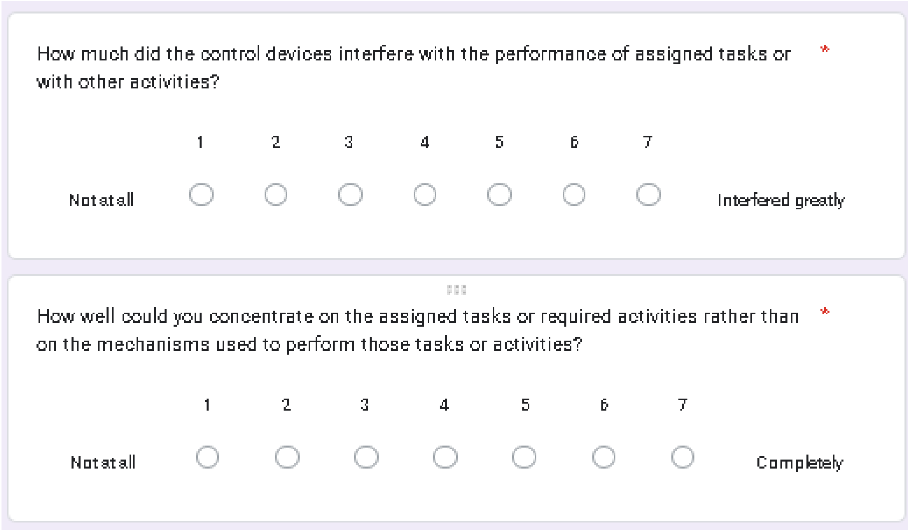
How proficient in moving and interacting with the virtual environment did you feel at the end of the experience? *

	1	2	3	4	5	6	7	
Not proficient	○	○	○	○	○	○	○	Very proficient

How much did the visual display quality interfere or distract you from performing assigned tasks or required activities? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Prevent task performance

Figure E.3: c)



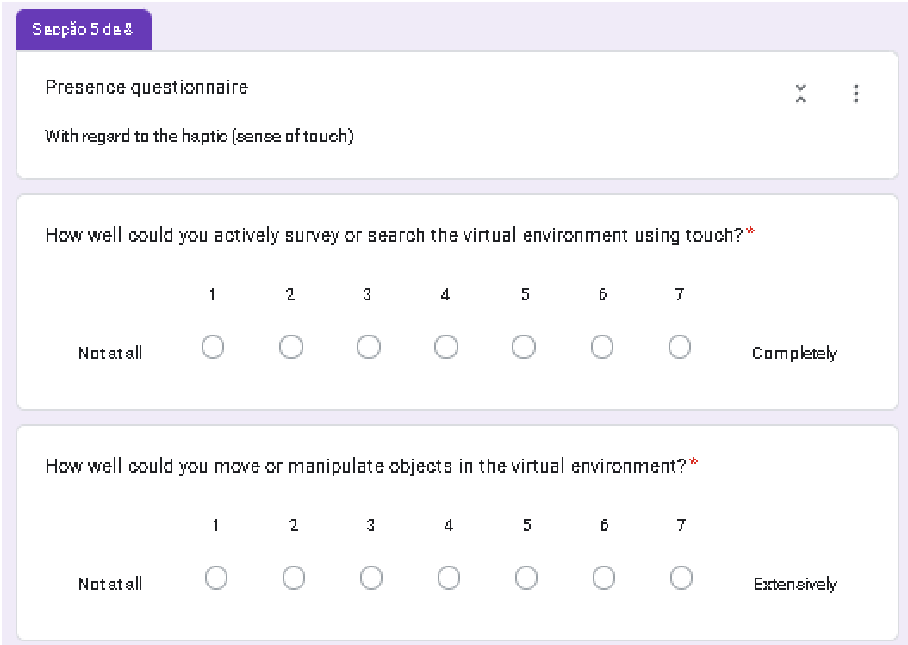
How much did the control devices interfere with the performance of assigned tasks or with other activities? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Interfered greatly

How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Completely

Figure E.4: d)



Secção 5 de 8

Presence questionnaire

With regard to the haptic (sense of touch)

How well could you actively survey or search the virtual environment using touch? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Completely

How well could you move or manipulate objects in the virtual environment? *

	1	2	3	4	5	6	7	
Not at all	○	○	○	○	○	○	○	Extensively

Figure E.5: e)

Appendix F

Presence questionnaire results

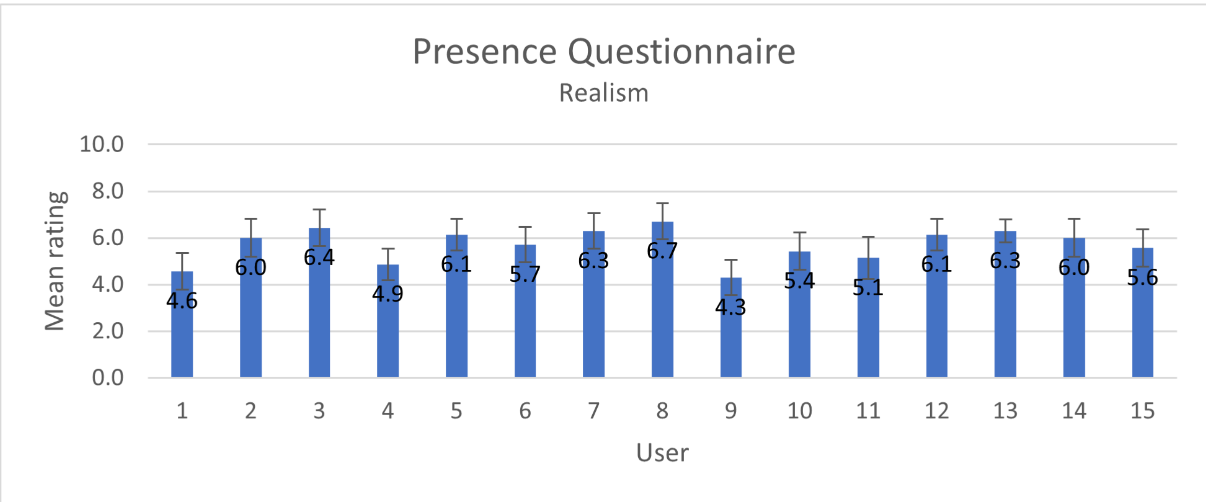


Figure F.1: Presence Questionnaire- Realism.

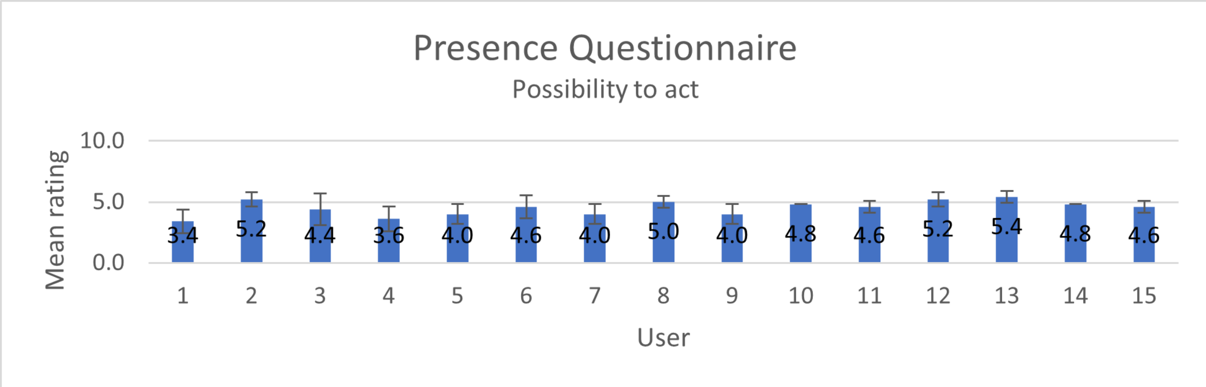


Figure F.2: Presence Questionnaire- Possibility to act.

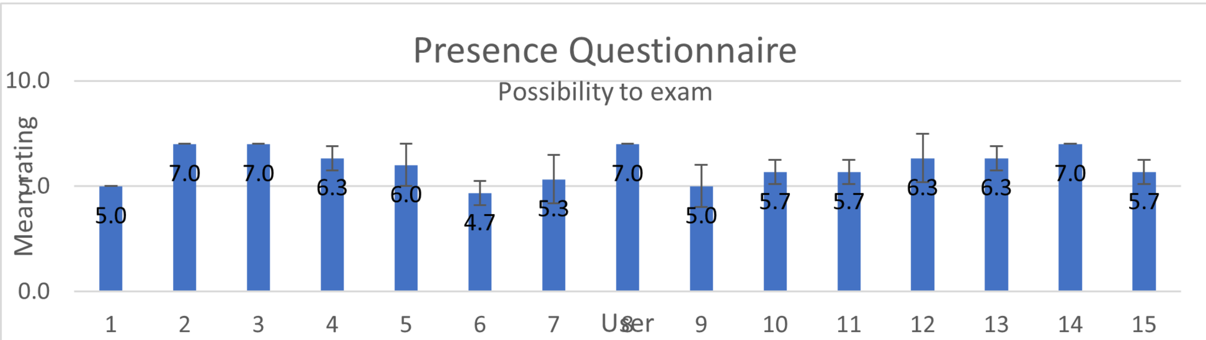


Figure F.3: Presence Questionnaire- Possibility to exam.

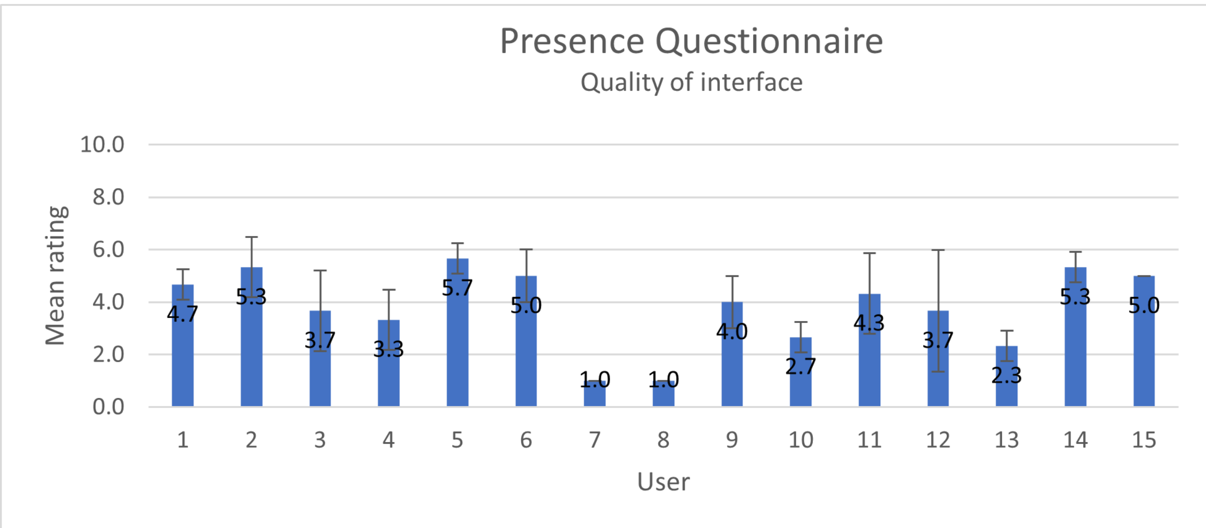
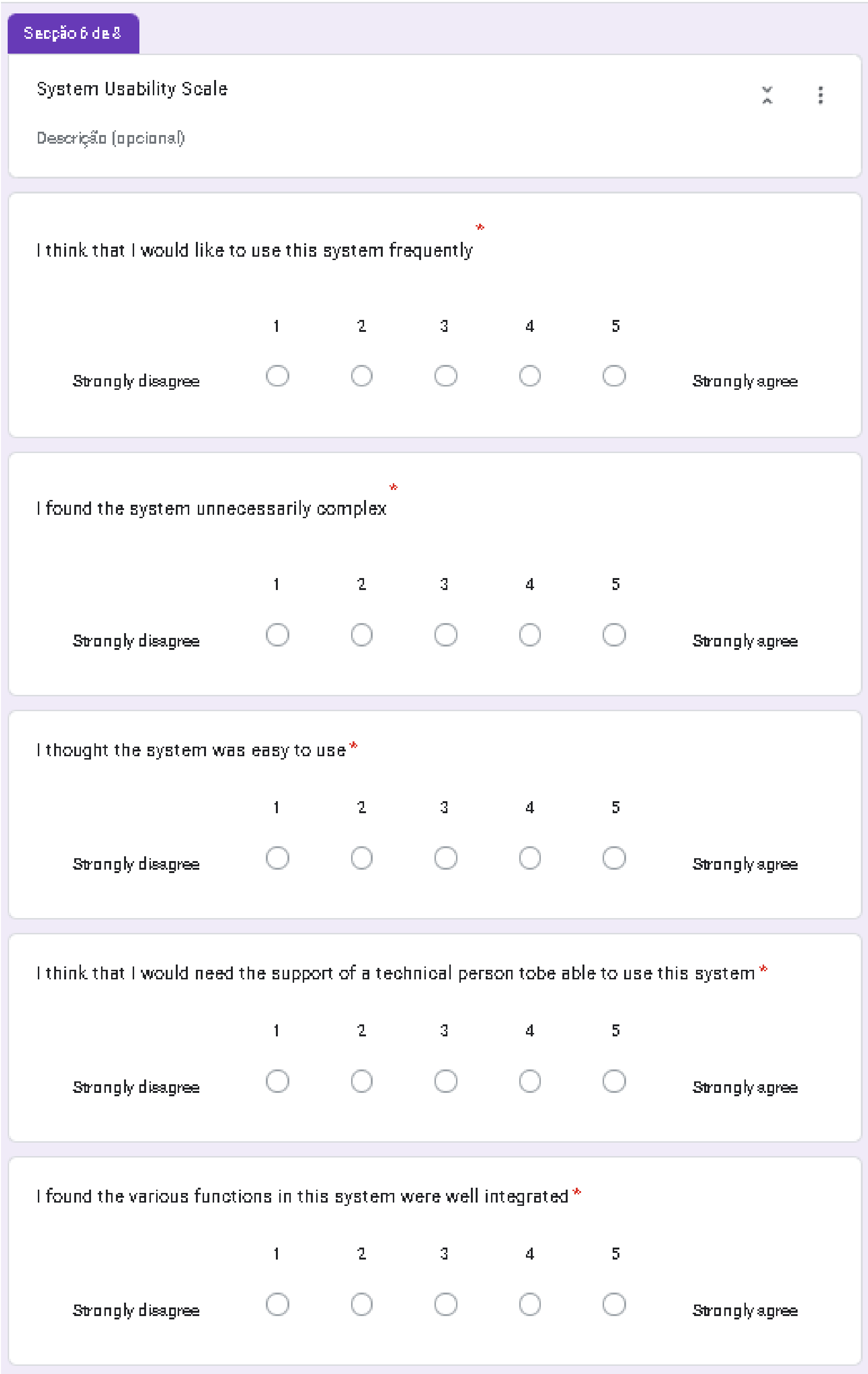


Figure F.4: Presence Questionnaire- Quality of interface.

Appendix G

SUS questionnaire



Secção 6 de 8

System Usability Scale

Descrição (opcional)

I think that I would like to use this system frequently *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I found the system unnecessarily complex *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I thought the system was easy to use *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

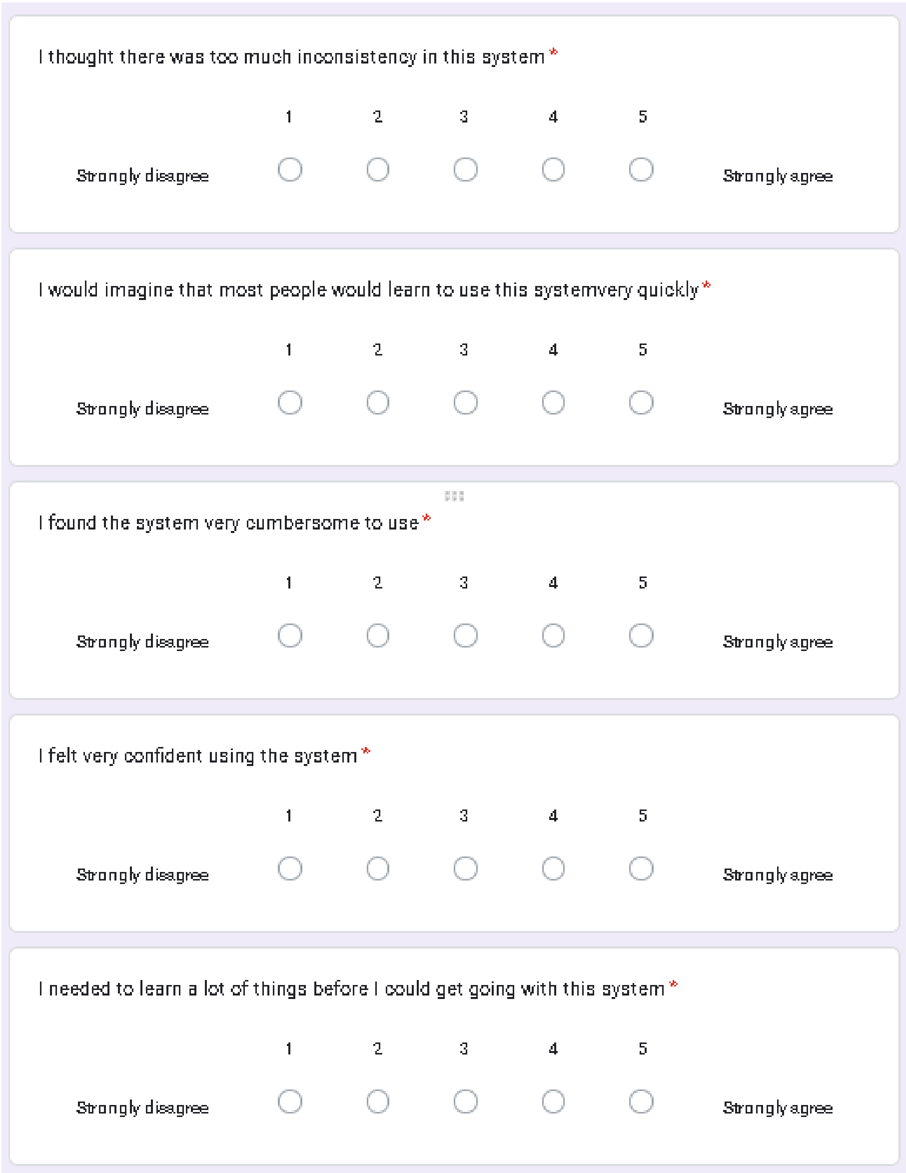
I think that I would need the support of a technical person tobe able to use this system *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I found the various functions in this system were well integrated *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Figure G.1: a)



I thought there was too much inconsistency in this system *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I would imagine that most people would learn to use this systemvery quickly *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I found the system very cumbersome to use *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

I felt very confident using the system *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

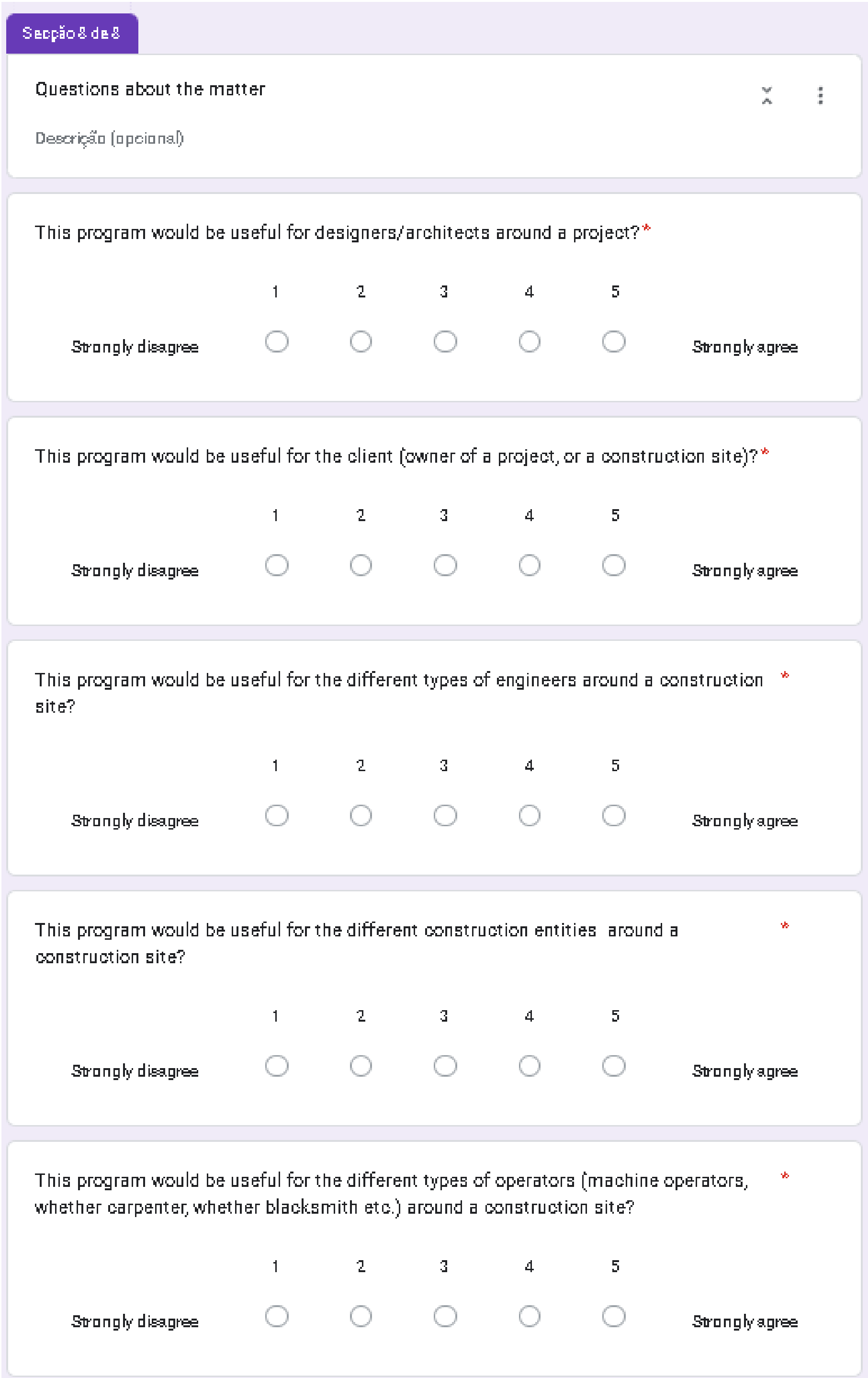
I needed to learn a lot of things before I could get going with this system *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Figure G.2: b)

Appendix H

Questions about the matter



Secção 8 de 8

Questions about the matter

Descrição (opcional)

This program would be useful for designers/architects around a project? *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

This program would be useful for the client (owner of a project, or a construction site)? *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

This program would be useful for the different types of engineers around a construction site? *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

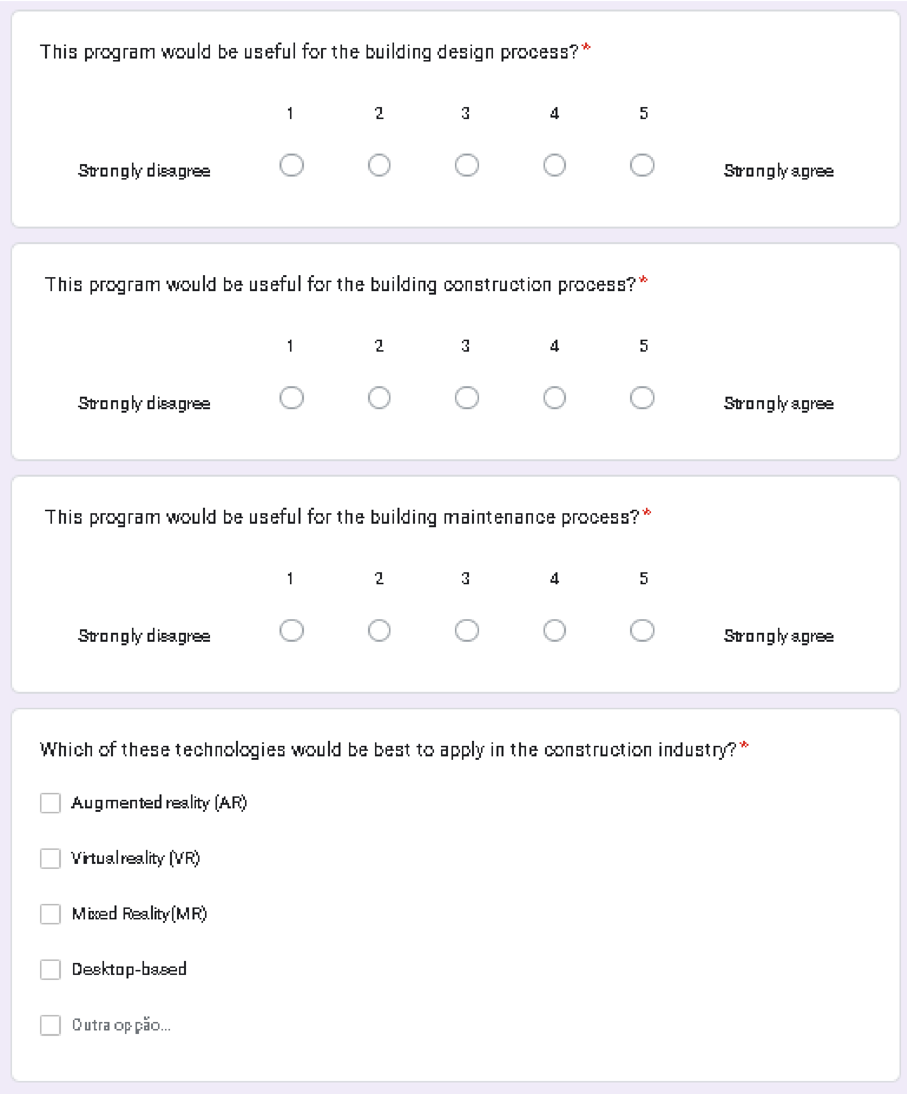
This program would be useful for the different construction entities around a construction site? *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

This program would be useful for the different types of operators (machine operators, whether carpenter, whether blacksmith etc.) around a construction site? *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

Figure H.1: a)



This program would be useful for the building design process? *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

This program would be useful for the building construction process? *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

This program would be useful for the building maintenance process? *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

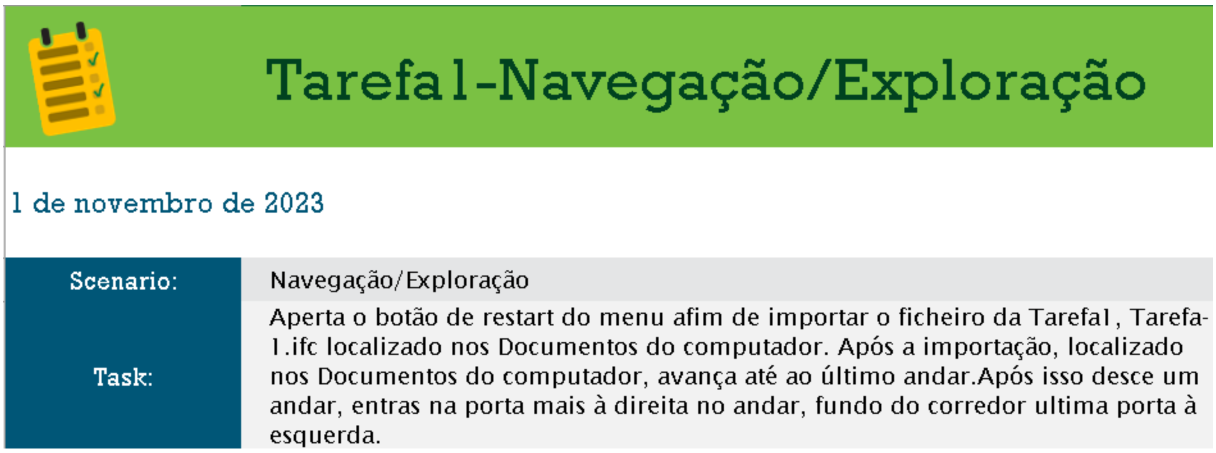
Which of these technologies would be best to apply in the construction industry? *

- ☐ Augmented reality (AR)
- ☐ Virtual reality (VR)
- ☐ Mixed Reality(MR)
- ☐ Desktop-based
- ☐ Outra opção...

Figure H.2: b)

Appendix I

User tasks



Tarefa1-Navegação/Exploração

1 de novembro de 2023

Scenario:	Navegação/Exploração
Task:	Aperta o botão de restart do menu afim de importar o ficheiro da Tarefa1, Tarefa-1.ifc localizado nos Documentos do computador. Após a importação, localizado nos Documentos do computador, avança até ao último andar.Após isso desce um andar, entras na porta mais à direita no andar, fundo do corredor ultima porta à esquerda.

Figure I.1: First task to the user.

Tarefa2-Consultar propriedades

1 de novembro de 2023

Scenario:	Consultar propriedades
Task:	Aperta o botão de restart do menu afim de importar o ficheiro da Tarefa2, Tarefa-2.ifc localizado nos Documentos do computador. Após a importação, localiza e seleciona a janela redonda no segundo andar e aplica um valor de 3 à propriedade FireResistance, vê a mudança a ser feita na listagem das propriedades.

Figure I.2: Second task to the user.

Tarefa3-Edição

1 de novembro de 2023

Scenario:	Edição do modelo
Task:	Aperta o botão de restart do menu afim de importar o ficheiro da Tarefa3, Tarefa-3.ifc localizado nos Documentos do computador. Após a importação, procura por uma parede vermelha e elimina-a. Posteriormente, encontra uma parede azul na parte de fora do modelo mais à esquerda no modelo e move-a para a esquerda aproximadamente 1 metro. E finalmente dirige-te à parede amarela na parte frontal do modelo e move a porta azul mais para a direita 1 metro.

Figure I.3: Third task to the user.

Tarefa4-Importação

1 de novembro de 2023

Scenario:	Fusão de modelos ao importar um outro modelo
Task:	Aperta o botão de restart do menu afim de importar o ficheiro da Tarefa4, Tarefa-4.ifc localizado nos Documentos do computador. Após a importação, encontra a parede laranja, e importa outro modelo Ifc localizado em Users->2087018->Documents->Wall.ifc, e posiciona-o à direita na parede laranja atrás do modelo.

Figure I.4: Fourth task to the user.

Tarefa5-Geração de um vídeo

1 de novembro de 2023

Scenario:	Geração de um vídeo
Task:	Aperta o botão de restart do menu afim de importar o ficheiro da Tarefa5, Tarefa-5.ifc localizado nos Documentos do computador. Após a importação, Com o recorrer à multi seleção seleciona o andar de cima do modelo neste caso o andar Story e pôe-o invisível. Após isso realiza um vídeo cinemático ao clicar no botão do menu com as definições padrão.

Figure I.5: Fifth task to the user.

Appendix J

VR guide

A quick guide to the VR application

General information

This VR application can be used using an HMD with its controllers or even from the keyboard with the mouse joint. When you start the application, it checks to see if any HMD is connected. If it isn't, it enables the HMD device simulator. In addition, this application contains an installation wizard.

Installation

When you open Setup, you are asked for the destination of the folder containing the files needed for the application [Figure 2], after which the files are created in the specified location.

Start the application

After installation, when you go to the submitted location, you'll find the following files visible in Figure 3. Inside them, open the "vr test" executable.

Controls)

Keyboard and mouse controls

Basic controls

Command	*Description*
Left Shift [Hold]	Manipulate the left-hand controller
Space [Hold]	Manipulate the right-hand controller
Mouse2 (Right Mouse Button) [Hold]	Manipulate the HMD
T [Toggle]	Toggle manipulation for the left-hand controller, you can use mouse input to either Translate or Rotate manipulated device(s)
R [Toggle]	Toggle between Translate or Rotate mode for mouse input
Ctrl [Hold]	Temporarily forces into Rotate mode while held
Mouse 3 (Middle Mouse Button) [Hold]	Temporarily forces into Rotate mode while held
Z [Hold]	Constrain translation/rotation/reset to z-axis
X [Hold]	Constrain translation/rotation/reset to x-axis
C [Hold]	Constrain translation/rotation/reset to y-axis
V [Press]	Reset position or rotation
— [Toggle]	Toggles between the mouse cursor being unlocked or locked to the game window
G [Hold]	Grip
Mouse 1 (Left Mouse Button) [Hold]	Trigger
B [Hold]	Primary Button
N [Hold]	Secondary Button
M [Hold]	Menu
4 [Hold]	Primary 2D Axis Click
5 [Hold]	Secondary 2D Axis Click
6 [Hold]	Primary 2D Axis Touch
7 [Hold]	Secondary 2D Axis Touch
8 [Hold]	Primary Touch
9 [Hold]	Secondary Touch The Vector2 controls on the controllers
1 [Toggle]	Toggles whether keyboard inputs apply to Primary 2D Axis
2 [Toggle]	Toggles whether keyboard inputs apply to Secondary 2D Axis
3 [Toggle]	Toggles whether keyboard inputs apply to HMD/Controller Position When Position is enabled
WASD [Hold]	Forward/Left/Backward/Right translation
QE [Hold]	Down/Up translation of the HMD/Controller
Mouse4 (Forward Button) and Mouse 5 (Backward Button) [Hold]	Up/Down of the opposite controller
IJKL [Hold]	Alternate input for Forward/Left/Backward/Right push of the opposite controller

Special controls

Command	*Description*
G	Select elements / Teleport action / Drag element
Mouse 1 (Left Mouse Button) [Hold]	Enable/Disable teleport / Interact with the UI / stop FP recording
M [Hold]	Show/Hide Menu

HMD controls

The controls can be seen in the Figure 1.

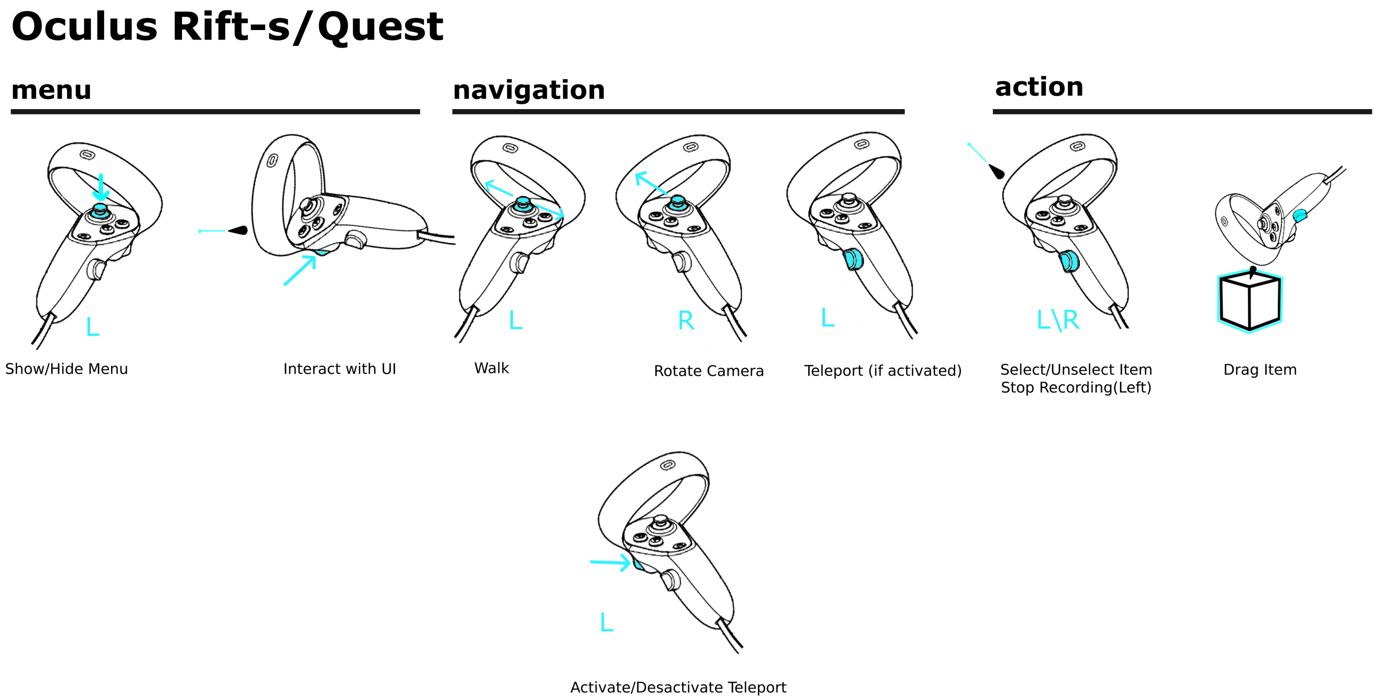


Figure 1: HMD controls.

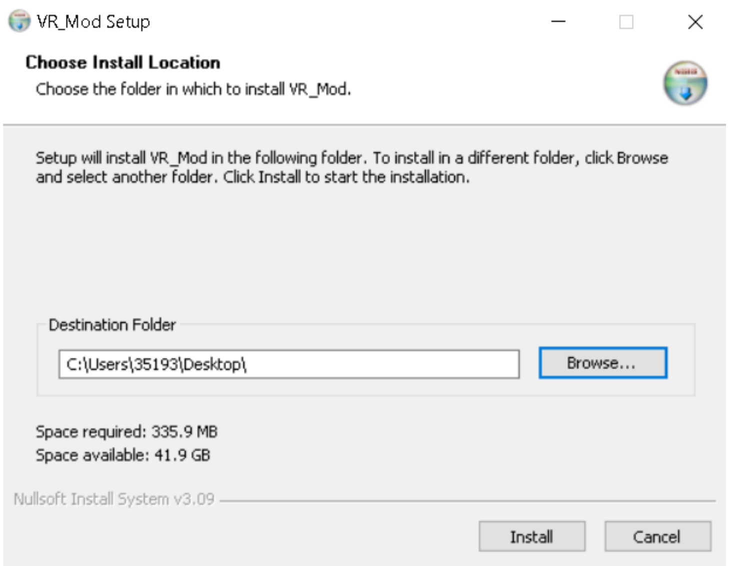


Figure 2: Installation Wizard.

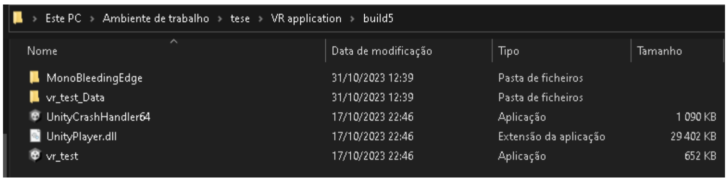


Figure 3: Resulting files from installation.