Integrating BIM, Virtual Reality and Serious Gaming for effective collaboration and communication between end-users and the design team

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Abstract

The literature review findings indicate that the traditional practices (drawings, 3D models, videos) to involve end-users and communicate the design intent to clients are still widely spread throughout the companies from the architecture, engineering, and construction industry. During interviews, professionals working in architectural companies confirmed the need for an active contribution of end-users/clients in a public building's early design stage. They inhabit buildings on a regular basis, and hence, their participation in project development is necessary for buildings’ performance and has the potential to reduce costs and time due to a decreased number of design changes later in the process.

The report investigates how the integration of BIM, Virtual Reality (VR), Serious Gaming (SG), and related technologies can help end-users and clients to express their viewpoint on design solutions. A prototype is developed in a game engine and tested with the project participants. It consists of interactive scenarios concerning the building’s functionality and accessibility, which can be used to obtain end-users’ requirements and essential feedback during the initial designing stages. The prototype testing shows promising results for improving communication and collaboration between the end-users/clients and the design team.

The research also includes current trends, results from the literature review, analyses of VR, and SG applications in the AEC industry, prototype design process - user-centered with adapted contextual design method and suggestions for future work that could improve further the simulation development.

Keywords
"AEC Industry", "Virtual Reality", "Game-based VR", "End-users", "Game-based learning", "BIM", "User involvement", "Serious Gaming", "Unity".

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Preface
This master thesis is a written record of a research project completed during the 4th semester of the master's degree in education in Construction Management and Building Informatics at Aalborg University in Aalborg, Denmark.

Documentation of the project consists of observations and the outcome of the research conducted throughout the semester. The process includes informative chapters with the theory about Building Information Modelling, Extended Reality technologies with a core focus on Virtual Reality, Serious Gaming, User Environment Design, and end-users' involvement in the design process. Moreover, presented applications of VR, AR, Serious Gaming integrated with BIM in the AEC industry provide an overview of different possibilities of improving collaboration and communication between end-users and designing teams, leading to extracting future occupants' requirements while testing the prototype.

On top of that, the project examines the AEC industry's current state via insights from the professionals. It supported the process of the solution development along with testing the prototype with users. References are found in the back of the report on page 108. The used sources are enclosed in square brackets [x] following the Institute of Electrical and Electronics Engineers (IEEE) style. The number inside the bracket corresponds to the source number in the reference list.

Symbols and Acronyms

AEC – Architecture, Engineering, and Construction

AR – Augmented Reality

BIM – Building Information Modelling

CAD – Computer-Aided Design

FBX – Filmbox file format

FM – Facility Management

HMD – Head Mounted Display

LOD – Level of Detail, Level of Development

MX – Mixed Reality

SG – Serious Gaming; Serious Games

VR – Virtual Reality

XR – Extended Reality

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Chapter 1. Introduction

The architecture, engineering, and construction (AEC) industry have been facing significant changes in working structures. Especially, **Industry 4.0** steadily revolutionizes construction with technological improvements by digitalizing and automating processes in production, collaboration, and communication between different professionals. [1] Moreover, the construction industry leans towards embracing even more computer and mobile-based solutions on the site as the new technologies advance. One of the main aspects is covered with the recent developments in viewing complex construction information in real-time. [2] It leads to growing needs for integrated solutions that could improve the industry even further.

Simulations, virtual and augmented realities have become popular over the years in industries such as medicine and healthcare due to the technologically suitable nature for training medical personnel, running different medical scenarios, or using them to support surgeries and treatments. [3] Furthermore, these technologies can be integrated into game-based learning concepts (*serious games*) for educational purposes in almost all professions to render the adequate flow of knowledge, for instance, in engineering, production, and even as an application in the military. [4]

Simulations and serious games can enhance the learning of the presented environments by allowing users to visualize, investigate, and interact with objects relevant to the purpose of so-called *Educational Gaming*. For example, it is visible in the *Architectural, Engineering, and Construction Industry* (AEC), where users can get necessary insights to improve problem-solving abilities that can further be adapted into real-world work. Such gaming simulation keeps learners motivated and engaged throughout the display of material on-screen or through specific equipment (e.g., virtual reality headset). [5]

Virtual, Augmented, and Mixed realities are adopted for an immersive design of buildings, objects, and machines. It includes understanding, reviewing, and experiencing 3D models before starting the construction. On top of that, these tools act as storytelling methods incorporated into games, products, or projects. Moreover, such techniques expand the horizons of BIM – *Building Information Modelling,* which provides essential value to construction processes and building projects to share and exchange data. It is also about the digital representation of a building with modeling the integrated design enriched by information. [6] [7]

Virtual Reality and Augmented Reality are implemented in various IT-based systems that lead to investigation issues in the collaborative BIM environment where knowledge is shared between the participants. These systems include exploring, for instance, health and safety aspects on construction sites, visualization of procedures in the risk zones, action simulations via walkthroughs to detect possible clashes, or training the workers to follow a specific management plan. [8] Furthermore, based on virtual reality and serious gaming, the designed platform provides sequences of educational activities such as fire safety procedures. For example, following escape routes in case of emergency and running different scenarios to see and experience how occupants of a particular area in a complex building could potentially react in case of real danger. [9]

Various research addressed a variety of purposes and use cases for VR implementation in the design and construction processes, and one of the main objectives for the application of VR in BIM-based design processes resulted in the need for enhancing the communication of design requirements and design review. [10] Moreover, other researchers demonstrate how virtual reality technology can promote collaboration through better communication and access to information for all stakeholders, regardless of their technical knowledge. For instance, it is shown how VR systems can support the demand side of the design process. Clients and end-users who may lack technical expertise can participate more efficiently in the decision-making process with immersive VR rather than using traditional methods for expressing information such as 2D drawings, renderings, videos, or presentations. [11] [12]

In construction projects, end-users are typically not qualified, and their knowledge of three-dimensional space is constrained. The challenge generally comes from the fact that users cannot visualize how the concept would appear during the development process. The inability of users to read drawings also affects them to specify the client brief. [13] The end-users are mostly but not only the potential occupants; there are also caretakers, technical workers in charge of services, or any other person whose operation could be affected by the building, who can express their wishes in the design of public areas. They all have limited experience and challenges in creating alternative spatial solutions themselves. [14]

Issues mostly appear when the users are ignored during the design stage, and this can have a negative effect because they are more sensitive and essential to the finished product. If the consumers contribute to the design process, they share a part of the responsibility with the design team and cannot fault them solely for any design issue. [15] In other words, when people believe they have power over their external world, they are more open to spatial exploitation, which enhances their happiness. According to [16] "end-user satisfaction is contingent not only on the outcome but also on the way it is achieved".

1.1. Problem statement

Design changes are inevitable in a construction project and will lead to increased time and costs. Even with nowadays technologies, these design "mistakes" are still happening worldwide. [17] However, practices from other industries start to be implemented in the construction industry. One of them is that the gaming industry combined with educational gaming has significant potential in learning easier and more efficiently different tasks, such as evacuation procedures, operating a building, or even staff working in the new building, like a hospital. [18]

While there have been many researchers developing frameworks of using Virtual Reality in the early stages of the design of a building [5] [12] [19], the literature review shows a lack of knowledge in regards of current software that can be used to enhance the communication and collaboration between the end-users, clients and the design team.

The problems outlined above and, in the introduction, form the basis for the need and purpose of this study. A problem formulation and one sub-question were established to view the research and development of the thesis in this area.

How can BIM, Virtual Reality and Serious Gaming be integrated to improve collaboration and communication between the design team and the end-users in the design stage of a public building?

Future occupants of buildings have unique perspectives on how their workplace should look and what the practical requirements are. Therefore, the goal involves the end-users and clients more actively in the early design process to minimalize risks of late changes. BIM and Virtual Reality, along with the related concepts and technologies, are the focus area for exploring a possible solution to improve collaboration and communication aspects stated in the above problem question.
Furthermore, VR is more investigated as a potential solution to formulate and describe the end-users and the clients' requirements and wishes that could be retrieved from an interactive simulation, thus to answer the problem formulation, there was a need to narrow it down into the following sub-question:

How can an interactive VR simulation of a construction project help the design team obtain requirements or wishes from the end-users and the client?

The above question and sub-question are analyzed and described using the tools mentioned in the next chapter of this report, Chapter 2. Methodology.

1.2. Aims and objectives

This report aims to discuss the end-users and client involvement in the design stage of a public building and possibly improve collaboration and communication with the design team.

This paper's main objective is to create a serious game that can improve communication and collaboration between the end-users/client and the design team. The game focuses on obtaining the future occupants' requirements regarding the interiors' functionality and accessibility to help the design team implement those requirements earlier in the building process and possibly reduce costs and time.

Before developing the game, the industry's current trends are analyzed through literature review and interviews of experienced professionals from Architectural and Construction companies in Denmark. Moreover, this data, combined with information from existing VR software and game engines, will create the basis for the game.

As the last objective, the serious game mentioned above is tested by end-users, while the authors of this report act as a design team to understand how and what information can be generated throughout this process.

1.3. Delimitation

The paper's original intent was to create a serious game and test it later on with participants to understand if any requirements/wishes can be obtained by engaging in this VR simulation. However, due to the Covid-19 pandemic, access to participants was limited in the period in which this report was developed. Hence, the report results might have been different if more individuals had participated in the testing.

The method used for developing the prototype, contextual design, was adapted to our project in the Design of the Prototype chapter, meaning it follows the same principles to some extent, such as the contextual inquiry process, which was reduced to only interviews with people working in the industry due to the timeframe given for this report.

Even though the problem presented in this report is general, world-wide, the focus is on Denmark's architectural companies, regulations, and practices related to this.

1.4. Project structure

This thesis was divided into eight chapters which contain the following content:

- Chapter 1 – Introduction establishes the thesis's context, defines the problem formulation, and presents its structure.
- Chapter 2 – Methodology presents the methods used to analyze the problem formulation and how this research was conducted.
- Chapter 3 - Literature review and the State of Art contemplates the involvement of the end-users in the design stage, information regarding BIM, immersive realities, and 3D modeling software and game engines currently used in the AEC industry and facilities management, as well as different applications for Immersive realities.
- Chapter 4 - Virtual reality tools for architecture and construction are presented in this chapter and reviewed by the authors of this report and set the prototype's base.
- Chapter 5 - Design of the prototype is based on an adaptation of the contextual design method, following to some extent, all the necessary steps before creating a prototype. It also includes the information gathered through semi-structured interviews from people working in the industry currently in Denmark.
- Chapter 6 – In the Prototyping chapter is presented the serious game proposed based on the research from this report followed by the testing with end-users and ending in the analysis of the results.
- Chapter 7 – Discussion and Future Development consists of deliberation on results and potential game improvements, possibly using people experienced with Unity and programmers.
- Chapter 8 – Conclusion chapter contains the answer to the problem formulation presented in this paper's introduction.

Chapter 2. Methodology

The following chapter provides a general description of the research and data collection methods to answer the initial problem formulation.

2.1 Literature review and State of the Art

To summarize the previous research on this topic, the literature review was conducted by evaluating scholarly articles, books, conference papers, and other sources relevant to the study area. The most used databases were Google Scholar, Scopus, Primo - the Aalborg University's database, and other databases ResearchGate and Science Direct. The method provides a foundation of knowledge on the topic, such as finding main ideas, conclusions, and theories, establishing similarities and differences, and identifying gaps in existing research. The literature review showed the relationships between previous studies, which provided the context for the problem formulation and placed this inquiry within the background of existing literature, making a case for why further research is needed.

The literature review was written as state of the art, meaning the emphasis was on the most recent research articles regarding virtual reality applications in the AEC industry.

The information was found using a set of Booleans such as "or", "and", Asterisk*, regarding the following keywords: "AEC Industry", "Virtual Reality", "Game-based VR", "End-users", "Game-based learning", "BIM", "User involvement", "Serious Gaming", "Unity". The resulting research papers, books, conference papers were chosen and assessed for relevance with attention to peer-reviewed articles, and relevant websites and tutorials were used. The referencing style IEEE was used to gather the sources directly referenced in this report. The bibliography mainly consists of research articles from journals, books, conference papers, and websites.

2.2 Semi-structured Interviews

For this paper, six persons from the Architecture and Construction field across Denmark have been interviewed. The interviewees have been chosen from a few cities in the country and from varying companies in sizes to overview the whole industry aspects concerning Virtual Reality, end-users' involvement in the design stage, and BIM.

This report's interview method is based on a framework (*See Figure 1*) for a qualitative semi-structured interview guide. [20] This interview method combines the structured and unstructured interview styles, which can offer the advantages of both. The semi-structured interview process includes open-ended questions and training of the interviewers to follow relevant topics. However, the interviewer can identify new ways of seeing and understanding the issue at hand. [21]

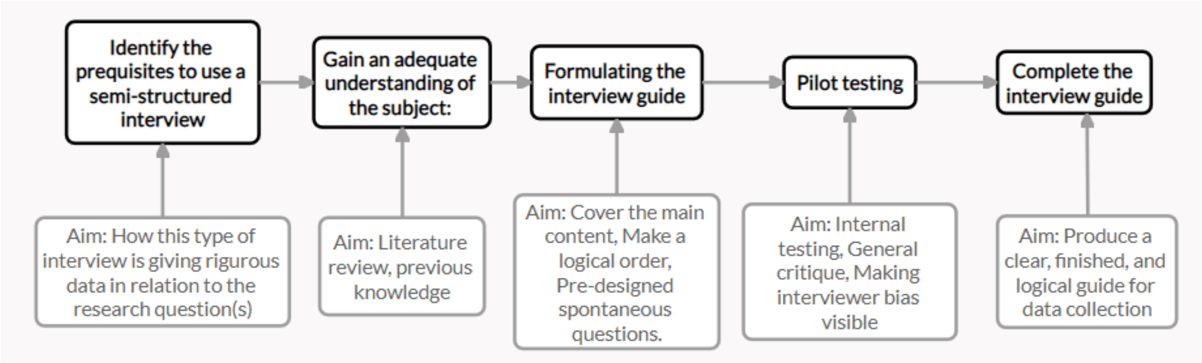


Figure 1 - Method for creating a qualitative semi-structured interview guide based on Kallio's framework [20]

There are a few approaches to analyze qualitative semi-structured interviews, such as textual, content, disclosure, and thematic analysis. After the interviews were conducted, the approach taken was to analyze them using the thematic analysis method, which helped find information about people's views, opinions, knowledge, and experiences in the field from this qualitative data set. [22] This set of analyses was using a semantic approach for analyzing the explicit content of the gathered data. [23]

2.4 Existing software review

The existing virtual reality tools used in the architecture and construction industry were reviewed by the authors of this report. The review was based on the specifications and features these apps include, which provided a baseline of knowledge needed for developing a VR simulation prototype for end-users in the Design stage. The process included searching for the most used VR software in the AEC industry, install them, and run a 3D Revit model of the newest building from Aalborg University. Thereby the programs were examined if the affirmations from their websites were functional in practice. The next step included mapping in tables all the different kinds of features provided by the programs and used them as a guideline for prototyping the VR simulation.

2.4 Contextual design

Contextual Design is a customer-centered design method that emphasizes a cross-functional team from obtaining data regarding customers in the field, via analysis and consolidation of the data, to the development of product models and a validated product framework. [24] This method begins by understanding that any structure represents a way of operating. The role and structure of the system require users to adopt complex strategies, language, and workflow.

The contextual design supports users' understanding in their natural environment, getting input about their drives, behaviors, and background through observations and conversations. The developing method is based on designing practical applications, IT systems, hardware, software, and other technological solutions. On top of that, Contextual Design can be implemented as a tool to teach user-based developments with human-computer interactions. [25]

Public buildings can be seen as software for specific users. Usually, the user's input can improve the outcome. Therefore, as in the development of programs, the user's involvement is an important part; the same basis must be applied in designing public buildings. [26]

Conceptual modeling was used to describe and represent the relationship between the different stakeholders within a construction project. In the context of collaboration and communication between the end-users and the design team, it provided an easily understood representation of the system for the different participants involved. In order to graphically represent this context, **the business process modeling notation (BPMN)** was adopted in the report for creating the organizational process of a construction project and finding out where the end-users could be integrated. [27] For a clear understanding of the figure diagrams from this report, the BPMN annotation was incorporated throughout different contextual design steps to express work models.

The main steps to consider while using Contextual Design are divided into three core categories with specific tasks to perform for user-centered design – **Data Collection and Interpretation**, **Consolidation and Ideation**, and **Detailed Design with Validation**. [28] *Figure 2* presents part I of Contextual Design with the adjusted principles for the project report. Each step was supplemented with the relevant description and the supportive questions to guide the prototype development.

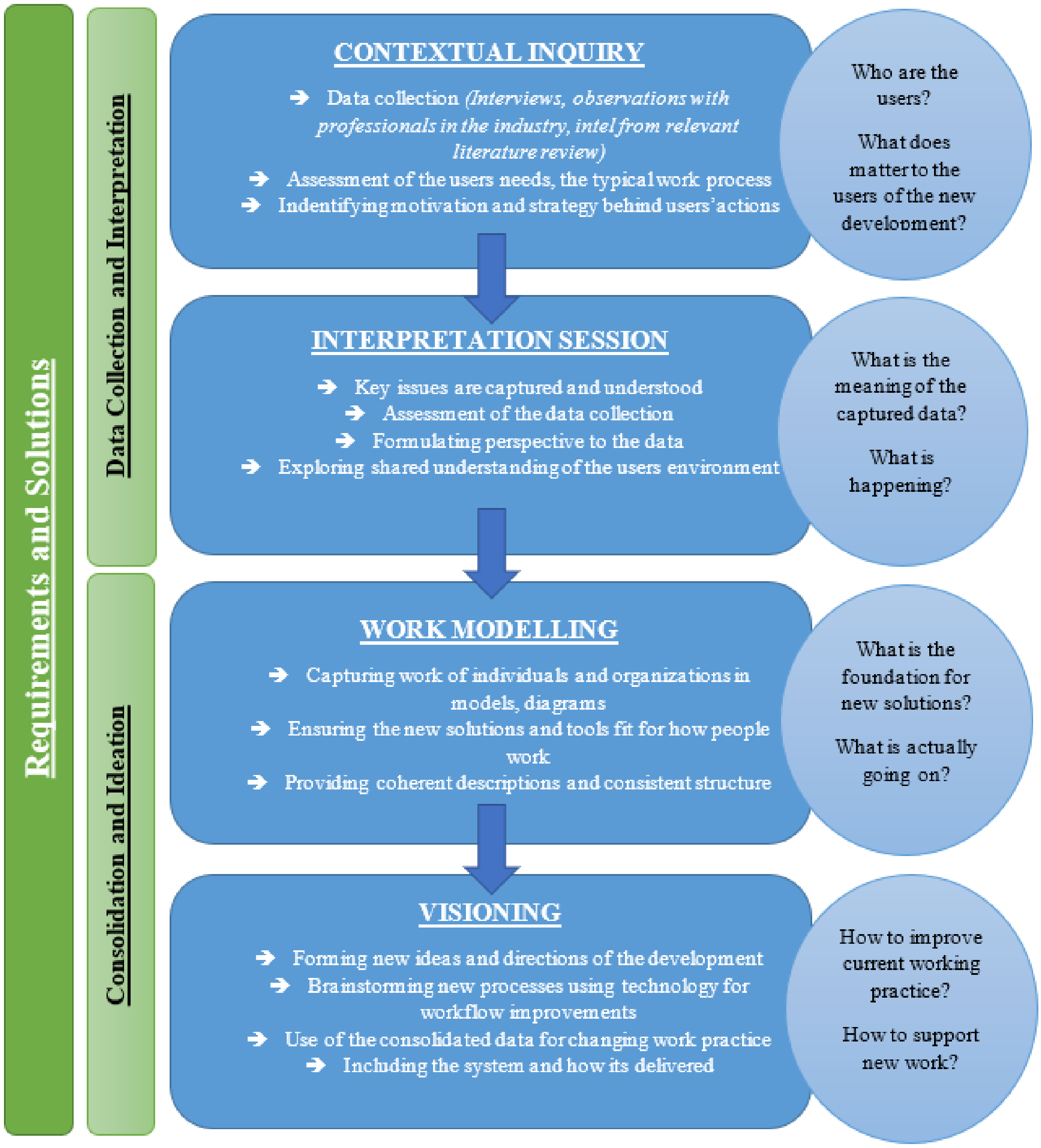


Figure 2 - Contextual Design Process Part I based on [25], [28]

According to Holtzblatt and Beyer, **Contextual Inquiry** is the first step of Data Collection and Interpretation where essential information about users is gathered during interviews and observations and is based on four core principles: Focus, Context, Partnership, and Interpretation. It was decided to use the original Contextual Inquiry as an inspiration for conducting interviews and gathering information due to the thesis's given timeframe and scope. Data collection about professionals (designers and architects) in the industry from the different companies was performed with semi-structured interviews to get a shared understanding of their working processes, which is usually involved, and what matters to the actors regarding a VR simulation development. It is essential to understand what they need, how their workday looks, and what drives and matters to them in completing various tasks. On top of that, relevant statements from the literature review were presented to extend the scope of views on involving end-users and clients in the design process. Furthermore, the **data was interpreted,** and the key issues were captured to make sense of what is happening in the industry and understand the collected data.

The work modeling process was adopted in Consolidation and Ideation to display in diagrams the work of individuals and groups or teams. The principles of flow model and sequence model were used along with BPMN annotations to map out organizations, actors, and processes and understand what is going on, how, and if end-users are involved in the designing phases. After understanding the users, the brainstorming sessions took place for proposing new solutions and processes to extend the current practice in the companies while at the same time using technology to improve workflow in the step called **Visioning**. Moreover, it was investigated how new work can be supported. [25], [28] The different components are connected to form new directions for developing the prototype. Two questions are in the center of visioning, focusing on how the new work can be supported and improve the current working practice.

Figure 3 shows Part II that describes the adapted methodology of the contextual design. The displayed procedures were adopted for the project to develop the simulation prototype effectively.

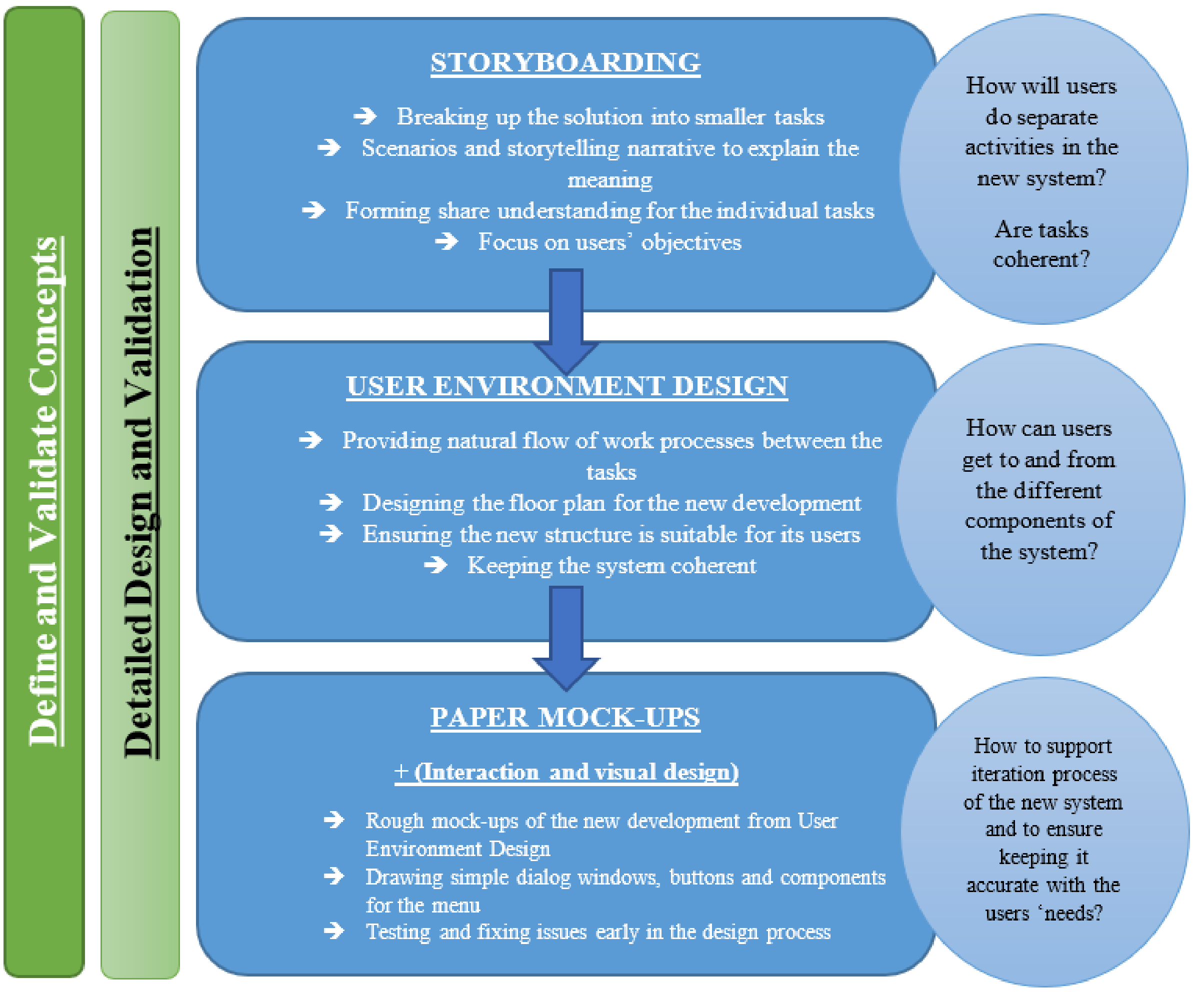


Figure 3 - Contextual Design Process Part II based on [25], [28]

Detailed Design and Validation were achieved with the **Storyboarding** – phase that is about describing with the help of graphical representations how users will do certain separate activities in the new working solution. Furthermore, **User Environment Design** was created to link different tasks from storyboarding into one coherent system to supplement the natural workflow. It can be described as the new **floor plan of the development** to guide the new working way. **Paper mock-up and visual design** were created as the next step for testing to iterate the new establishment with the users. The paper prototyping was tested with four students from Building Informatics at Aalborg University and four other individuals working in the AEC industry. [25], [28]

2.5. Prototyping and testing

The prototyping involved adding a test model into Unity and create a serious game using different assets and a few scripts. This simulation was based on the Design of the prototype developed in Chapter 5, and with tutorials of using Unity and various scripts.

The prototype, presented in Chapter 6, was afterward tested with six participants. In the beginning, the test users were presented with the project case and the prototype's details. It included the plan for the testing sessions and how to navigate in the simulation – complete seven levels of the game, and test in VR designing and annotation tasks. 3D model in Autodesk Revit was shown to them, along with floor plans and the project's description. Shortly after, a Questions & Answers session was held when they could ask about the model and overall process.

Furthermore, they were asked to answer a set of questions during and after the testing. These questions were created based on the literature review, the interviews of the professionals, and the paper prototyping feedback gathered at the end of the Design of the prototype. The testing results were presented at the end of Chapter 6 and served as this report's results.

Chapter 3. Literature review and the State of Art

3.1. Involvement of the end-users

Communication between designers and customers at the briefing and design level is usually based on the client's requirements and the designer's solutions shown in *Figure 4.* The project brief should identify all the design specifications and shape the framework on which the design will be built. In general, the design process is dynamic, and there is continuous contact between the brief and the design proposals. [29]

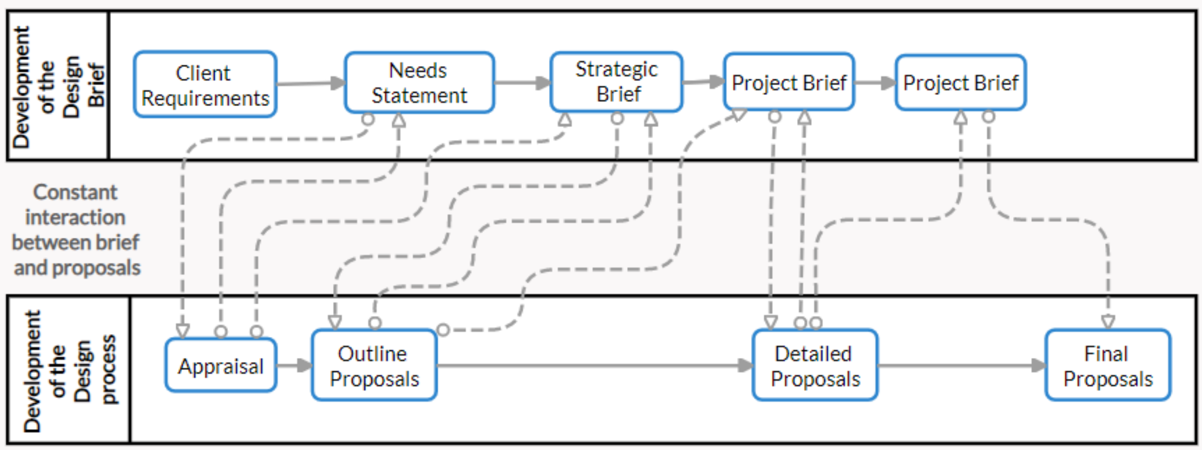


Figure 4 - The process of Brief and Design phase based on [29]

In the design process, architects frequently anticipate user behavior with less consistency because the interaction between users and spaces is dynamic. In comparison, architects will hardly be able to test their projections until the occupancy phase, in which it is usually costly to repair the architecture. As a result, in tandem with improved computing capabilities and intense development activities to model connections between users and spaces, architects have been equipped with modeling resources that can provide appropriate input from virtual users during the design phase. [30] In a building, the energy consumption is also closely connected to user simulations. The energy demand projection can vary by more than 150%, with various user activity values calculated by experts. [31]

The goal of user involvement in the early design of the building is to increase the usability or create a final product that will function for its users. [32] However, Kujala [19] describes that user involvement increases both the efficiency of product development and the consistency of requirements, which influences the functionality of the product, i.e., the usability of the structure. The advantages of including users can be much broader, such as supporting a positive user mindset towards the project and the design team's work. [33]

Users are either directly or indirectly involved in the project. For example, the user-centered design requires a comprehensive understanding of users, but it is not always necessary to include users directly in the process. [34]

Some user involvement techniques are used more frequently in the AEC industry than the manufacturing industry due to AEC projects' particular features. For example, in comparison to the manufacturing sector, users often do not appear before occupying the building, except in situations where the clients are also end-users. [35]

It is challenging to include users in all construction projects and provide a design concept that can help people appreciate the structure and have input close to the experience they would have in their profession. Therefore, users have been modeled as digital agents who engage in offering simulated input on design decisions. [30]

While the manufacturing sector has been researching the significance of end-user needs for decades, it highlights the construction industry's " deficiencies in meeting the consumer's needs." End-user satisfaction is a challenging factor to evaluate: a combination of technical and functional (quantitative) and emotional and contextual analysis (qualitative and heavily based from one user to another). [19]

3.1.1. The users of a public building

The user may be referred to as an end-user, which means that the "end" is the completion of a building, i.e., when it will be used for its intended purpose. For example, the users of the office building would be those who use the building as a work environment; the users of the school building will include those who attend classes as students; those who attend school as employees (i.e., teachers, maintenance workers), and those who attend school at open events, such as parents; hotels would have different types of users, hospitals as well, etc. [36]

Building users can be very diverse, and therefore, they may have different requirements. It is also extremely imperative that all user parties are adequately addressed when designing a brief and layout for a new building or improvements to an existing building.

The end-users of a public or complex building are especially employees and people who need to do specific tasks in the building, such as students. Therefore, the needs of these individuals refer to the excellent conditions of a workplace environment. According to Clements-Croome & John Derek [37] the physical environment of the worker's workplace influences its productivity and happiness. He also stated that the facility's design, which includes the location and configuration of the equipment inside the building, is a primary element responsible for the physical environment at their workplace, in situations where individuals are not happy with their workplace, affecting how they perform their duties.

For the workplace to be perceived as performing, it should be designed to maximize the staff's efficiency. It means that building a public space and fulfilling the criterion that is considered the right workplace environment. It is essential to analyze the individuals who work there and understand the processes underlying their everyday activities. [38]

3.1.2 Design Requirements and Building Regulations

In this subchapter, the Design requirements are discussed according to the building regulations in regards to functionality, accessibility, and safety of public buildings to have an overview of what needs to be kept in mind while designing public buildings and to ensure a working environment for the future occupants of the building.

On a broad scale, in the paper of Philip Ayuba [39], several types of public buildings have been analyzed regarding the ease of space identification, the ease of movement within the building, the facilities' arrangement, and the adequacy of private space. Their findings show that end-users of public buildings are usually not happy with the construction and design decisions. In terms of space requirements, the staff considered the spaces insufficient because they found it almost impossible sometimes to carry out their everyday operations.

In a more narrowed-down situation, Dragana Nikolic [40] conducted interviews and tests with a VR prototype with Designers, Public clients, End-users, and Accessibility experts, to use this input for an immersive VR representation for design review. Some of the design requirements they found during their study were the functionality and effectiveness of internal spaces of innovative schools, which included: "*Functionality of building spaces concerning their use, Effectiveness of building spaces to ensure innovative learning methods, accessibility and safety of circulation paths, and adaptable grouping of similar spaces.*" In other words, from the interviews, they found out the design requirements regarding functionality and accessibility, used afterward for enhancing the prototype.

Therefore, design requirements are explicitly based on the building type and what it will be used for after completion. Users are dissimilar for different projects, as well as their tasks are not the same. Nevertheless, the environment in which they will be performing their duties must meet their needs as close as possible to a functional, accessible, and safe workplace. Chapter 9 from Building Regulations in Denmark stated that in buildings where there are organized workplaces, these rooms must be designed with the size, sunshine, room height, and the content of the room, to ensure it is used by several individuals who are expected to work there, with considerations of health, safety, and functionality of the room. [41]

The general specifications from Building Regulations regarding public buildings' layout present general rules for different facilities to ensure the accessibility and functionality for the building's end-users. It also explains rules for elevators in shared access paths, where the end-users must have unassisted access to the building's levels and functions. [41]

The fire and safety regulations are playing a crucial role when designing any kind of building. The entire Chapter 5 from BR18 explains general rules for ensuring safety in buildings, guidelines on fire safety installations, requirements for these installations, and escape routes for the evacuation of persons. [41]

BR18 is mentioned in this report because the end-users/client most likely do not know any of these regulations, and so if they engage in a virtual reality simulation, they might not notice if these rules are met. Therefore, the design team must ensure that the BR18 regulations are met concerning functionality, accessibility, and safety of the buildings' interior and are integrated into the BIM model. In other words, for example, the sprinkles, firewalls, fire doors do not necessarily need to be present in the 3D model because testing the building with end-users does not require a high level of development. However, later in the building's design development, if a team member or the fire inspector wants to check the building, then the model must include all the objects in place according to the BR18.

3.2. Building Information Modelling

Building Information Modelling (BIM) has been an essential part of many construction projects over a few decades. It has come closer to be recognized as a standardized norm in the working culture. BIM enables effective communication methods between the AEC projects' stakeholders as a coordination tool, visualization of digital data platform, and sharing medium between the participants. [42]

The common practice over the years in the AEC specializations has been involving communication and collaboration between professionals over 2D drawings leading to a large amount of paper documentation and fragmentation of the delivery process. Responses to these issues included implementing a 3D-based designing program and databases acting as storage units for project information. Such solutions do not guarantee improved processes in the industry alone. That is where Building Information Modelling comes up. [43] As an innovative technology and collaborative process, BIM has been rapidly changing the AEC industry with its approach for project stakeholders to see a building in the simulated environment before it is built. [44]

Based on scientific research papers, books, and related publications, BIM can be defined as both **revolutionary technology and a process that changed the principles of how projects are developed**. In other words, BIM is a digital representation of a building that reinforces the use of software; It is about the automation of the processes, visualization, integrated project delivery, refers to improved communication between stakeholders; [44], [45], [46]**,** [43], [47], and to n-D modeling (3D consolidated model, 4D also includes time simulation, 5D with added costs estimations, 6D with sustainability and analyses, 7D with incorporated facility and management applications) [48] [49].

BIM advocates and assists in keeping track of all data for the entire life cycle of a building, meaning the information can be shared at any point, updated, and maintained by everyone involved. [50] Furthermore, this technology is thought-out as the core of digitalization in the AEC industry, involving sharing and data visualization to help with possible modifications in the project's design and construction. [46]

BIM refers to many standards, definitions, and interoperability purposes supported by international organization buildingSMART that enable a collaborative environment of shared knowledge among all stakeholders. Standardization and specifications to promote solving interoperability issues and improved collaboration specification include among others: IFC - Industry Foundation Classes (neutral-based format typically applied for exchange of information), Information Delivery Manual (captures and specifies necessary processes), Model View Definitions (subset from IFC schema, specified use to fulfill exchange requirements), BIM Collaboration Format (facilities open communication between tools, software), and buildingSMART Data Dictionary (provides access to various standards). [51]

Implementation of BIM principles, methods, and integrated design can result in cost reduction, shorter duration of any project, and overall quality improvement. [52] It contributes to providing more efficient project control and more effective collaboration with clearly stated roles of every team member compared to the manual process done traditionally. BIM supports processes within procurement, cost assessment, visualization, and design development with analyses and the fabrication of building elements, construction, and facility management. BIM is also an application in quality management, construction site logistics, and supply chain management. 3D object-oriented models enriched with individual data and precise geometry of every component are constructed digitally to represent an accurate physical equivalent. [53], [49], [43]

On top of geometrical representation and property data, information-built models in the BIM environment are usually supplied with spatial relationships between its components, quantities for cost estimations, and project schedule. [53], [54] The schedule can be incorporated for creating animation (known as 4D design) that presents construction tasks completed on the building following the planned time. Such a feature can help designers and contractors understand complex processes or to deliver them to the client. [50], [44]

The application of BIM in the AEC projects improves not only collaboration between professionals from the different disciplines but also communication with clients. Furthermore, it is easier to predict building performance and find clashes with the shared models. [53] The idea behind collaborative BIM models is that any modifications are continuously updated for other team members to see almost instantly. Involved parties can then investigate if the new changes affect their specialization work. [50] Integrating BIM is one of the stakeholders' central answers to meet the growing demands in the industry. [55]

3.2.1. BIM and End-Users involvement in AEC

Building Information Modelling and Facility Management (FM) offer technological concepts that support collaboration methods for integrated design, construction, and maintenance processes. [50] BIM is an innovative technology that supplements the AEC industry with effective processing, storing, exchanging, and managing data throughout buildings' whole life cycle. The manual input is replaced with continuous information flow between involved team members, companies, or other professionals. [45]

On top of that, BIM allows actors without prior technical knowledge to visualize based on the input from the 3D informative display of models from the initial designing stages. These digital displays are found to be more effective than traditional methods of 2D drawings. However, only a few practices could potentially supply designers with tools to increase productive interactions for working with clients and end-users and provide functional, active measures. [50] End-users are usually future daily occupants with an essential experience-based contribution [56], administrative, operation, and maintenance employees, or outside service suppliers of a certain project [57]. Different backgrounds of these users can lead to varying views on the needs and expectations of a building they are about to occupy regularly, visit, live, or work in. Thus, it is an essential part of the design process to build up profiles of different groups of people.

A successful project is when it lives up to its role and expectations – the building is constructed and furnished with the intended design purpose to fulfill end-users' requirements and needs. [57] The design phase of any project holds the paramount impact from decision-making to change and influence the outcome. Thus, the technical composition needs to reinforce different participants' diverse skills: architects and construction specialists, the clients, and the end-users. [58] The future occupants are in a significant position as they hold necessary insights into a particular building's usability and functionality. The extraction and translation of their knowledge depend on how comprehensive and consistent the method is regarding user involvement. [57] It can be interpreted as the projects' outcome relying upon a complete understanding of users' background and intended use of all spaces by the designing team.

Commonly, it is adopted that the design intent is communicated through physical models such as cardboard mock-ups, images from 3D-based software, or even with walk-throughs [56], on top of demonstration techniques with models, drawings, and videos. [59] However, clients usually receive a formal presentation with a static and passive type of information about projects without any interactive form. The potential of active contribution during the design phase has not been recognized yet as a standard practice even with BIM practice on the functional level. [50]

For example, a presentation for the client usually only includes prepared information and models with corresponding views of drawings displayed on screens or paper. It might lead to situations that the demonstration of a project is rather what the designing team thought the client wants to see rather than what the intended user wishes to explore. [50]

The needs and requirements can be revised by the design team, together with the end-users to extract their unique point of view. It is significant to keep the users motivated and allow them to express the ideas freely to understand the building's real intent thoroughly. [57]

Clients' and end-users' involvement could bring more effective and efficient results if they were more actively involved in the process. The architects would not have to continually change proposals because of poor communication with clients, static presentations, or not including end-users in the development. [50] More and more technical possibilities have been appearing in the industry, already acclimated for years 3D modeling with BIM, collaboration platforms, or other digitally advanced tools that could help designers and end-users find united ground for the building design. [57] Various ways are being investigated to enhance BIM processes even further. The integration of BIM and VR could be the answer to positively impact the AEC industry and improve communication, design visualization, and overall decision making. [58]

3.3.2. BIM software and animations tools

3D sketching methods, visualization of BIM models, and compatibility with VR solutions via plugins can be found in a growing number of software providers, to name a few, Autodesk Revit, Graphisoft ArchiCAD, and Trimble, offer project development in the BIM environment. [60]

Autodesk was established in 1982 and became popular due to the development of **AutoCAD** software. The computer-aided design platform has enabled more automated work in the AEC industry. Currently, it offers designing 2D and 3D drawings and is still widely used worldwide. However, AutoCAD's position has been replaced by another product of the company, **Revit**. The software company offers building information modeling and management for professionals in the industries of AEC, manufacturing, and MEP (mechanical, electricity, plumbing). Autodesk also provides animation and design visualization tools such as **3Ds Max** and **Maya**, software that can create detailed 3D content for game development, highly detailed renderings of the buildings, and even movie effects. [61], [62] It is also worth mentioning that an alternative free solution for animation, rendering, and modeling 3D objects for games or digital representation of building elements is possible with **Blender** software. [63]

Trimble is a company that also supplies the AEC industry with different BIM technology solutions for the entire lifecycle of buildings. [64] It includes **SketchUp** for an architectural design where ideas can be modeled into 3D digital representations [65], and **Tekla** for model sharing and BIM's practical focus on structures. [66].

ArchiCAD, established by Graphisoft, a Nemetschek Company, is another famous supplier of technological solutions for BIM, especially for architects' and engineers' integrated design workflow [67].

On top of the leading BIM products, the professionals can use **Solibri** and **VICO Office** programs. Solibri enables BIM processes optimization by tools of model viewer and checker, IFC Optimizer, and clash detector. Solibri Checker, for example, generates a BIM Collaboration Format (BCF) that can be returned to modeling software for adjusting the model based on detected issues. [68] On the other hand, VICO connects designing phases with the construction stage with products that simulate construction work with costs, control, and schedule. VICO Office enables quantity and material types take-offs from 2D drawings and 3D models for analysis and estimations. These BIM 4D (time, resource management) and 5D (cost management) solutions can be integrated via a plug-in to modeling software suppliers (e.g., Autodesk, Graphisoft, Trimble) [69], [62]

3.3.3. Level of Detail and Level of Development (LoD)

The level of detail of the Building Information Modelling increases as the project proceeds, mostly based on the first instance of factual information, from basic concept purpose model to a complex simulated development model, to a fully digital constructed information model. [45]

The level of development concept is integrated into BIM to allow construction players in the Architecture, Engineering, and Construction industry to define and express high-level design clarification and reliability of 3D models at different phases of the project. LoD is linked to the level of detail, representing the number of details used in the elements of the building model. [70]

LoD is the degree to which the geometry of the element and the relevant details on the components were regarded by the construction players when using the model. This implies that LoD is the degree to which project team members will rely on knowledge while simultaneously using the model. In essence, Level of Detail is an input to the element, while Level of Development defines reliable output. [71] [72]

LoD is represented by five different levels: LoD 100, which does not contain much information about the object and is usually used for basic estimations, pre-planning, and feasibility studies; LoD 200 is starting to have the accurate quantity, size, shape, location, and orientation of the generic object, and at this level, the analysis on performance can be conducted for choosing building components. The next level, LoD 300, must contain precise information in terms of quantity, size, shape, and location. It can develop the instructions for LoD 400, which is used to fabricate and install the elements. The last level, LoD 500, must contain the full, accurate digital representation of the final product. [73]

For this report, the end-users must visualize and feel like they are close to a possible real-life scenario for more accurate results. The LoD plays a considerable role in developing a simulation in Virtual Reality.

3.3.5. BIM integration with Virtual Reality and Game Engines

Building Information Modelling (BIM) and **Extended-Reality Technologies** (Virtual and Augmented Reality) have become more popular as applications, concepts, and methods to communicate the AEC projects to their users. [42] BIM enhances the use of technological solutions and promotes exploring new opportunities for better results in the AEC processes that enable more effective collaboration and analyses of the building models. [49] Adopting extended-reality technologies is linked to BIM for transforming the AEC and FM industries into a more digital character. Virtual Reality provides similar principles to BIM in product design, allowing for visualization of detailed entities before they are constructed in reality. [40] [74]

Various approaches can be integrated with BIM to enhance even more practical and effective management processes in the AEC industry. One of the research sectors that is being investigated recently in the AEC industry involves the use of the game engines for prototype development or VR on top of virtual models created in the BIM environment. Virtual and Augmented Reality technologies are relatively new in construction [42]. They have not been wholly exploited yet, as there is still a lot of potentials to be utilized. [1] Both BIM models and VR experience can support the understanding of building projects through careful planning and making it easier to discover errors and clashes in the early stages of design development. [54]

The reasons behind using game engines in the AEC industry are to create a Virtual Reality experience, serious gaming scenarios, simulation, or prototype for improving collaboration, design review, or overall workflow. BIM models consist of geometry data that can be incorporated for architectural visualization and numerous modeling-based programs allow creating visual aspects for building and construction. However, there is a lack of interactive features for the users, and the display is considered static. That is why Virtual Reality and 3D game engines are areas of research for use in the AEC industry. VR and the gaming industry's development can provide immersive depth to the BIM models and interactive experiences with both first and third-person perspectives. [75], [76], [47]

Xiong et al. [76] proposed a framework for utilizing both geometric data from a BIM model and a mechanism from a game engine (Unity) into an interactive and learning-based environment. Moreover, the researchers connected an online database (MySQL) to a game engine for displaying real-time sensor information on the site about room temperature.

3.3. Digital game-based learning

Game engines have been put in the spotlight of stakeholders' attention as a potential means to increase productivity and create an immersive environment for high-quality visualization with multiple users' experience at the same time. Moreover, game engines are currently recognized as the source to deliver application solutions quicker and less expensive, thanks to the available options and controls that do not necessarily require instant programming knowledge. [55]

Game engines are suitable for creating an immersive 3D environment based on BIM models (thanks to designing capabilities and 3D modeling nature). These programs contain intuitive controls that do not necessarily require prior coding knowledge. Computer game engines' abilities have been more frequently adopted in the AEC industry over the last years for the development of various prototypes and simulations. [50]

3.3.1. Game-based learning, Serious Gaming

Game-based learning, in other words, Serious Gaming (SG), is a form of a video game with an aim focused on learning outcomes that come from testing and playing simulations. Instead of only entertainment factors in usual games, the emphasis is put on serious themes of education, training, healthcare, and emergency simulations. Users of these games can engage with the elements and receive feedback for their actions. [77] One of the other purposes of Serious Gaming is the adoption of education in immersive VR applications. SG scenarios and VR immersion can address the gap from the static or low engaging forms of preparation for emergencies. [78].

Seminars, banners, evacuation drills, and educational videos are typical examples of teaching users' behavioral responses. [79] However, these methods are not sufficient enough, do not meet learning outcomes, and are not taken seriously by the users leading to inappropriate behaviors during real emergency events. Another reason is that occupants are not emotionally invested during, for example, evacuation drills, and they may find the overall experience from this form of practice unrealistic. [80]

3.3.2. Game engines applications in the AEC industry

According to research on the Steam platform, Unreal, Unity, idTech, Source, and CryENGINE are recognized as the most popular game engines. Besides the purpose of developing 2D, 3D, and VR games, the game engines are applied for architecture, medicine, meteorology, geology, and education. [81]

Yan et al. [47] mentioned game engines: CryEngine, Unity, Virtools, Max Payne, Quake, Quest3D, Torque, Counter-Strike Source, Unreal in their research for integrating BIM and gaming for real-time visualizations. These engines have been acknowledged in solutions for the AEC industry and related topics.

Torque game engine was appointed by Wyeld et al. [82] for supporting the creation of cultural heritage relics in real-time in a 3D virtual setting. Moreover, Scorpio et al. [83] utilized Unreal Engine to assess VR capabilities for lighting design while Hilfert & Konig [84] used the same engine for constructing a VR platform with IFC based system. On top of that, the chosen HDM involved Oculus Rift with the Leap Motion hand-tracking device.

Xiang et al. [85], and Frohburg & Petzold [86] chose Quest3D for an interactive development that involved 3D real-time simulation and educational purposes of architectural design, respectively.

The Source Engine (utilized in games Counter-Strike: Source and Half-Life 2) offers a wide range of facial expressions, flexibility, and advanced navigation for detailed characters. [87]. The engine was also used for behavior research in displayed virtual environments. [88]

CryENGINE was employed by Manyoky et al. [89] for developing realistic 3D animation of wind farms based on GIS-data and for supplying connecting parameters of simulation and locations in the model. The virtual environment consisted of detailed visualizations of vegetation, lighting, shadows. CryENGINE is found to be a suitable platform for producing high-quality graphics. The engine includes a Sandbox world editing system and an integrated toolkit for development. [87] However, the engine may have performance limitations noted in Hubert Zukowski's publication, who compared Unity and CryENGINE. Unity was spotted to perform better when similar applications were created in both engines. The indicators for the comparison involved CPU, RAM usage, and time necessary for 3D elements generation. [81]

Unity game engine is identified in publications for numerous solutions in the AEC industry. For example, Kysil [60] incorporated VR as a conceptual research and education tool by using the game engine; Osorio-Sandoval et al. [55] proposed a Discrete Event Simulation model by employing Revit, Unity, SharpSim with C# programming language tool, and Simphony.Net 4.0; Boston [90] developed 4D BIM simulation in VR using Revit, 3Ds Max, Navisworks, Unity and added MS project timeline; Castronovo et al. [5] established VR serious simulation game for a design review in Unity where students investigated mistakes; on the other hand, Svidt and Sorensen [56] used created VR prototype in Unity for involving end-users in interior design – the participants wore Oculus Rift HMD, could change room area, and move objects in the game.

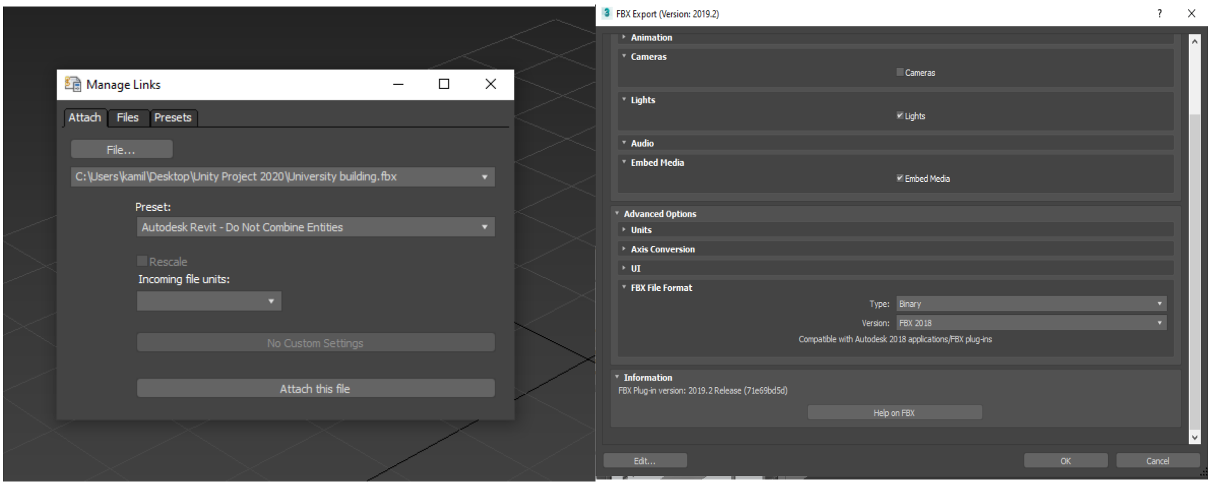
The literature review points out transferring challenges from modeling software to a game engine. Today, (2020) export process from a program such as Autodesk Revit requires additional consideration, either by plug-in solutions or middle point platforms, that can convert materials and texture in a readable manner by a game engine. Directly transferred FBX file from Revit to Unity results with only 3D geometry of a building without any materials and textures assigned to the structure. [76] [75]

Various publications refer to a workflow that consists of the 3Ds Max program as the optimization solution between the BIM model from Autodesk Revit and a game engine such as Unity. Moreover, incorporated C# programming language in a Visual Studio assigned to Unity allows creating animations and features on top of a model. [60], [91].

3.3.3. Export from Autodesk Revit to Unity Gaming Engine

As stated in the previous subchapter, literature publications suggest 3Ds Max as a modeling medium before importing models to a game engine. The reason behind this is to optimize the FBX file and adjust materials and textures to be presentable for gaming simulations. [76], [92]. A model made in Autodesk Revit, ArchiCAD, or similar BIM-based software can be exported to **3Ds Max** as an FBX file for adjustments to materials and textures. The prepared model can then be imported to a game engine (such as Unity3D) to develop the simulation. (*Figure 5* displays a few procedures, specifying preset of Do Not Combining Entities and export FBX file window from 3Ds Max) Detailed steps for exporting via 3Ds Max can be found in *Appendix C*.

Figure 5 - 3Ds Max export as FBX file after the optimization process shown in Appendix C



Alternatively, the use of various plug-ins is possible for the easier transfer from a BIM software to a game engine (Examples for Autodesk Revit: GLTF Converter, OBJ Converter, Export to Unity, AT+Sync – plug-in that also enables synchronization with Unity) [93] However, most of these solutions are paid extensions or offer only a trial version.

There is also a free plug-in that can be incorporated for Revit - ***Twinmotion 2020*.** [94] It is a relatively new option for importing the file as FBX. A high-quality model with its materials and textures can be implemented into a game engine with just a few specifications. It provides an easy workflow to follow that does not require many steps to start working in Unity3D or Unreal Engine. (Shown in *Figure 6*)

Nevertheless, 3Ds Max software has modeling options that, together with the incorporated material database, allows preparing objects or entire buildings to be put as ready graphically products. The merge option can be chosen similarly to the export procedures presented with 3Ds Max – By Family, by material, or no merge of the objects in the model. Twinmotion works not only with Revit but also with ArchiCAD, SketchUp, and Rhino.

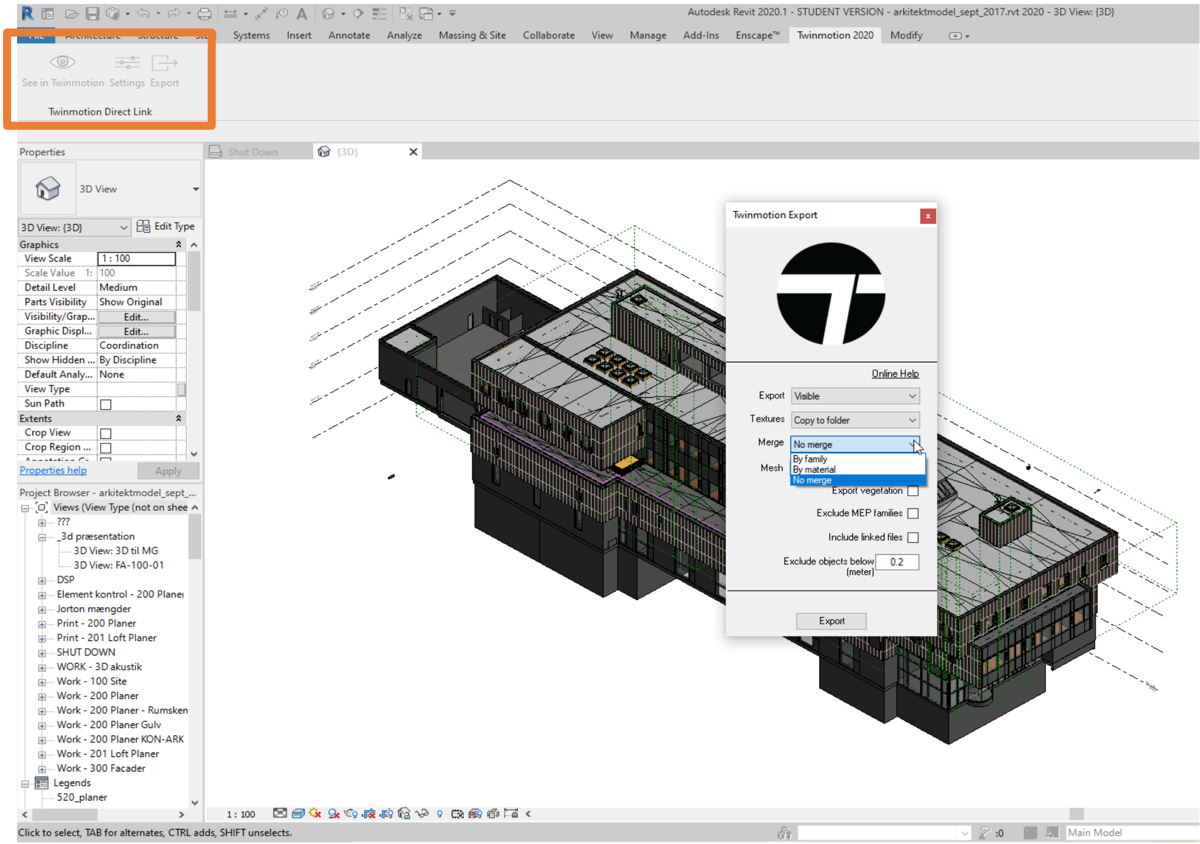


Figure - 6 Export from Revit via Twinmotion 2020 plug-in

Instead of using 3Ds Max, **Simlab Composer** (software for visualizations and VR development) might be applied as a solution to import a model effectively to Unity. For example, an FBX file is exported from Revit and put to Simlab Composer, then all the needed textures and materials are imported to a model. [95] It renders high-quality elements and relatively easy workflow to follow. However, it is also paid software. Therefore, it depends on resources and personal preferences to use different programs for creating ready models for game engines.

As an alternative solution to using a game engine, Unity offers a simple product for the AEC industry - **Unity Reflect**. It is a real-time BIM solution for 3D experiences with immersive technologies (AR, VR), desktop, or mobile viewing. A model can be imported via plug-in from Revit, BIM 360, Navisworks, SketchUp, Rhino. Any changes to a model can be synchronized to Unity Reflect. This paid solution enables collaboration and design review. [96]

There is also a free plug-in called *Walk-Through-3D™ for Autodesk ® Revit®* [97]. It allows exporting the Revit model as a .exe file that corresponds to an already automatically built game from Unity3D. It takes a while to process the entire model, but after it is complete, the standalone game is offered. The users of this extension can walk freely through the building as the first-person perspective character, use weather and lighting features, change materials and textures, and colors (only updated in the model prior to using the add-in). It is a useful tool for the designers who want to test their proposals fast without building by themselves a simulation game in Unity.

3.3.4. Serious Gaming applications in the AEC industry

SG has been getting more and more attention in recent years. On top of applications in healthcare, driving, emergency simulations, learning, teaching, health, and safety at work, SG has been applied to the related disciplines' work to the AEC industry. [78]

Applications of serious gaming or simulation games for the AEC industry includes developments such as monitoring and operating inside virtual models in real-time with access to an online database for information management [76], reviewing design scenarios for healthcare facilities [75], interactive architectural visualization in the real-time "Design-Play" process [47], architectural, historical reconstruction [98], game-based learning in building services, mechanical and civil engineering [99], and more. The table below demonstrates studies centered on developing solutions in game engines.

SG and game engine-based applications in the AEC industry – a literature study			
Reference	**Problematic statement**	**Solution**	**Conclusion**
Developing an Experienced-based Design Review Application for Healthcare Facilities Using 3D Game Engine **[75]**	Investigation of providing interactions and reviews for users in real-time.	3D game engines are incorporated for managing scenarios and design review in the healthcare facilities.	The proposed system with a game engine allows interactive experience for task scenarios.
Using 3D Design software, BIM, and game engines for architectural-historical reconstruction **[98]**	Exploring 3D design programs and game engines for digital reconstruction.	Results from various reconstruction cases and design approaches are investigated to use BIM with a game engine.	It is possible to develop real-time architectural visualizations for historical reconstruction.
Serious games as a virtual training ground for relocation to a new healthcare facility **[18]**	Investigation of how BIM and serious gaming can be integrated to supply professionals in the learning outcomes about the spatial understanding in new buildings and preparation for facility management.	Theory, BIM model, and serious game approach are tested with a case study – hospital in Norway and interviews with the different stakeholders (clients, software providers, professionals).	Challenges are met with exporting and importing between BIM and a game engine. Training and communication improvements are highlighted.
An overview of game-based learning in building services engineering education **[99]**	New learning methods are investigated to help and motivate engineering students. Lack of game-based learning for building services is noticed.	Game-based learning is implemented with competition and rewards. Educational methods for building services are reviewed.	Learning outcomes, motivation, and engagement can be increased when the game simulations real-life tasks.
BIM and Game Engine Integration for Operational Data Monitoring in Buildings **[76]**	Providing an interactive layer to BIM's capabilities for stakeholders and mobile use.	The 3D game engine and BIM are integrated to overcome limitations for real-time monitoring. The development is based on serious game principles and tested with a case study.	The proposed system allows users to go through the modeled building, check and understand materials and MEP systems and operate in real-time.
Integration of Building Information Modelling and Discrete Event Simulation within a Game Engine **[55]**	Proving the benefits of BIM and Discrete Event Simulation in the construction industry and how it can be combined with the game environment	A simulation prototype using a game engine is developed with educational tasks for construction.	This promising development showed an advantageous alternative to learning construction tasks that could be applied for education purposes

***Gaming Approach to Designing for Maintainability: A light Fixture Example* [91]**	Research for improvements for operation and maintenance during facility management.	A gaming engine is used to support facility managers for the involvement in the design phases. Their knowledge helps the improvement of designing tools. Functionality and usability are also displayed.	The findings suggest the feasibility of incorporating gaming engines in the design review, checking accessibility, and capturing decisions. The effectiveness of the BIM tools can be, therefore, improved with facility management involvement.

Table 1 - SG and game engine-based applications in the AEC industry

More serious gaming solutions are presented in chapter [3.4.1.5. VR applications for the AEC industry] - when applications are not only integrated with BIM models but also with Extended Reality technologies.

3.4. Extended Reality Technologies application in Architecture, Engineering, and Construction

Extended-Reality expresses all-immersive (sense of presence) technologies with interactive environments that put together physical and virtual entities. The phrase refers to all currently available advancements on the market (**Virtual Reality**, **Augmented Reality,** and **Mixed Reality)** and any possible future developments in this sector of engaging innovations. Based on recent studies, immersive technologies hold promising potential to become more accessible and mainstream in the upcoming years. The market for immersive environments is predicted to arrive at approximately 209 billion dollars by 2022. Furthermore, it could lead to unimaginable changes in the industries that use XR before 2030. [100]

A detailed review of Extended-Reality Technologies is presented in this chapter. Literature, publications, and insights from the professionals are discussed to form a clear overview of the AEC industry's available solutions and potential opportunities to investigate.

3.4.1. Virtual Reality

Virtual Reality varies from the traditional user-interfaces of looking at the displayed screen. Instead, the technology puts its users inside a created 3D world. The most evident element of VR is the head-mounted display. The most dominant HDM equipment as of 2020 includes *HTC Vive, PlayStation VR, and Oculus*. [101]

Virtual Reality is described in the book Virtual Reality Systems as "*the illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on three-dimensional (3D), stereoscopic, head-tracked displays, hand/body tracking, and binaural sound.*'' [102] In other words, instead of being an observer of the displayed world, users can have an engaging feeling with all their senses.

On the other hand, Dictionary Cambridge defines Virtual Reality as "*a set of images and sounds produced by a computer that seems to represent a real place or situation*" [103]. Another dictionary refers to the technology as "*a realistic and immersive computer simulation of a three-dimensional environment, created using interactive software and hardware, and* *experienced or controlled by the movement of the body*." [104] The modern definitions circulate about portraying VR with few key-take-away descriptive marks: **an interactive and immersive experience, representation of realistic features and worlds in 3D simulations, use of specialistic hardware (head-mounted and computer-generated image**.

Even though many definitions state that VR needs to be interactive, numerous computer-generated systems are not engaging but still considered VR solutions. Similarly, 3D movies, 360-degree videos, or any other display program only offer a viewing experience but can be recognized as VR simulation. [105]

VR systems enable the presentation of objects' visual character and information normally not visible in the real environment. [59] In other words, entities such as properties of components performance indicators or any other BIM data could also be displayed onto the virtual environment and objects.

When looking at the Virtual Reality concept's beginnings, the meaning needs to look at and also investigated from a broader point of view. The next sub-chapter provides an overview of historical developments that lead to what is now known as Virtual Reality. It is then followed by explanatory chapters of software development components, VR types, and applications in the AEC industry.

3.4.1.1. VR background and historical events

If looking at Virtual Reality as an illusion of entering another dimension, then even 360-degree murals and panoramic paintings made in the 19th century could be considered as part of what had led to the beginnings of the immersive solutions. [105]

The Virtual Reality's origin is considered with the first formed description of stereopsis (3-dimensional perception, sense of immersive depth) in 1838 by Charles Wheatstone. The study focused on proving that if each eye sees an image of the same element taken from a different spot than the other eye, then the viewing experience is immersive. The earliest prototype was called - **The Wheatstone mirror stereoscope**. The device used two mirrors placed at a 45^{o} angle reflecting photos (one reflection for each user's eye). [106], [107]

This viewing approach was later incorporated for the toy, children - the View-master [107]. It was patented by William Gruber in 1939 and found its application not only as a kid's toy but also as "virtual tourism." Moreover, the system's principle can be seen in Google Cardboard, a low-cost VR headset for mobile phones. Similar stereopsis development was introduced in 1849 – the lenticular stereoscope by David Brewster. [105].

The immersive technology's origin can be seen not only in technical prototypes behind VR creation, panoramic paintings, or computer-generated videos but also in literature. The science fiction story *Pygmalion's Spectacles* by Stanley Weinbaum in 1935 was about a character wearing special goggles that could be used to see virtual worlds, movies with a composition of senses, sounds, smell, touch, and taste. [106], [108]. The phrase Virtual Reality can be tracked as early as 1938 when mentioned in Antonin Artaud's literature. He referred to a theatre as Virtual Reality in "*The Theatre and Its Double*."

Regarding the 3D interactive environment, Jaron Lanier recognized VR when his company was responsible for building the first prototypes of goggles and gloves for VR experience in 1985. [54] [106]

Morton Heilig created **Telesphere Mask** in 1960. It was the first-ever head-mounted display that offers stereoscopic-television 3D with sound for individual use. [109], [110] Morton Heilig was also responsible for a huge multi-sensual simulator in 1962, **The Sensorama.** At the time of the system presentation, it was considered to be the most realistic duplication of reality. For instance, the user could ride a motorcycle in New York-based on the displayed colorful video and be accompanied by the generated wind from a fan and stimulated sound and smell of New York's scenery. However, the system was not interactive. [102] Morton Heilig was named „Father of Virtual Reality" in numerous publications after introducing the Sensorama. [110] For example, in the article Industrial Design in 1964, the system was described as a 3D sensation for the viewer. The Sensorama could be bought for 6000 dollars at the time. [111]

Ivan Sutherland (known as the *father of computer graphics*) contributed to virtual reality development with the publication "The Ultimate Display" in 1965. [112] [107] It describes the system as the artificial virtual world by integrating all the senses, force-feedback, and interactive computer graphics. Furthermore, this research led to the construction of *Sword of Damocles*, a VR system completed in hardware and not only in concept. [113] The device is considered the first head-mounted display (HMD) for VR and AR. It was too heavy for people to wear; thus, the prototype was mounted to the ceiling. At the time, the graphics only displayed wireframes of boxes for spaces and objects. The head-tracking was available – the view updated depending on where a user looked at. [107] The gigantic equipment was connected to a computer instead of a camera to render the virtual world. Moreover, the computer graphics were spread on top of the real-world entities [102]; [105]

1966 was the year when VR found its application as the first flight military simulation by Thomas Furness. It caused the growth of interests and funding for immersive technologies that could be used for training. [106], [108] Later, in 1982, Thomas Furness developed a Visually Coupled Airborne Systems Simulator for Air Force. The simulator allowed pilots, for instance, to display the augmented view with underlaying information about among other threats information, flight path, and identification data. The advanced flight simulator contributed to understanding technical requirements for effective VR systems and simulations and necessary features such as fat tracking with short lag periods, visual upgrades with textures and shadows, motion and force feedback, and different techniques for efficient display of multi-layered worlds. [102]

Another development for the flight simulators includes The Super Cockpit in 1986, pilots supported with better decision-making features, and 3D maps. A user wears a special helmet, gloves, and suit to access the immersive virtual world. The system consisted of voice and head-aimed control, touch panel, and even eye control feature [114].

Virtual Reality history up to the present		
Year/s	**Description**	**Reference**
1838	**The Wheatstone mirror stereoscope** prototype	[106]; [107]
1849	**The lenticular stereoscope** by David Brewster	[105]
1935	The science fiction story "*Pygmalion's Spectacles"* by Stanley Weinbaum was released where a character used goggles to enter a fictional world.	[106]; [108]
1938	Virtual Reality term used in "*The Theatre and Its Double*" by Antonin Artaud – Theatre described as Virtual Reality	[54]
1939	The View-Master by William Gruber	[105]; [107]
1960	**Telesphere Mask** – first HMD for stereoscopic-television	[109]; [110]
1961	**Headsight** – first motion tracking device by Comeau and Bryan	[105]; [108]
1962	**Sensorama –** multi-sensual simulator	[102]; [110]; [111]
1965	The Ultimate Display – concepts for interactive computer graphics display system	[113]; [102]; [112]
1966	**The first flight simulator** by Thomas Furness	[106]; [108]; [105]
1968	**Sword of Damocles** - Sutherland's first-ever VR/AR head-mounted display	[102]; [105]; [107]; [113]
1971	GROUPE – force-feedback prototype by University of North Carolina	[113], [115]
1972	180-degree field vision flight simulator by General Electric Corporation	[106]
1975	**VIDEO PLACE** by Myron Krueger – first interactive VR system	[106]; [113], [116]
1977	Aspen Movie Map by MIT – users were able to walk in a virtual setting of Aspen city	[102]
1982	**Visually Coupled Airborne Systems Simulator**	[102] [113]
	Sayre wired gloves by Sandin and Defanti for hand movements (beginning of the gesture recognition)	[106]; [105]
1984	**Virtual Visual Environment Display** by NASA Ames	[102], [117]
1985	**VPL** (Virtual Programming Lab) company was founded by Jaron Lanier and Thomas Zimmerman – the first company to market VR equipment (products such as DataGlove, EyePhone HMD, and the Audio Sphere)	[54] [106]; [113]; [105]

1986	**The Super Cockpit** simulator	[114]
1987	The phrase Virtual Reality became mainstream and wide-spread due to Jaron Lanier and VPL studies	[106], [108]
1989	**Virtual Environment Workstation Project** – training platform for Astronauts by NASA	[106]; [105]
1991	**Virtuality** – VR arcade machines, 3D immersive games for entertainment with VR goggles, multiplayer options; Medina's VR Mars Rover by NASA	[106]. [108]; [105]
1992	**CAVE** – VR and visualization system without HDM but with displayed images on the walls	[113], [118]
1992	**Virtual Fixtures by** Louis Rosenberg, first AR prototype system	[119], [120], [121]
1994	**CyberMaxx** (VR headset) and **SEGA VR-1** (a motion simulator arcade)	[106]; [105]
1995	**Virtual Boy console** by Nintendo (first console with 3D graphics, only one year on the market)	
1997	**Virtual Vietnam** – for treatment of PTSD by Georgia Tech and Emory University	[122], [108]
1999	VR technology popularized with The Matrix movie	[106]; [107]; [108]; [105]
2001	SAS Cube – PC cubic room	
2007	**Google Street View** introduction by Google and Immersive Media (started with five mapped cities)	
2010	**Oculus Rift** headset prototype by Palmer Luckey	
2014	Google Cardboard, Project Morpheus – VR for PlayStation, Samsung Gear VR	
2016	Mass production of VR equipment by many companies, e.g., HTC VIVE SteamVR with a sensor tracking	
2018	Standalone VR without computer or phones (Oculus Go and Oculus Quest)	[105]
2020	Standalone VT without computer or phone (Oculus Quest 2)	

Table 2 - Virtual Reality history up to the present

It can be concluded, based on historical events and background on immersive VR technology, that user-experience to give a sense of being in another place and interacting with virtual objects is at the core of the advanced solutions. VR came a long way to become what it is known today. With technology becoming more mainstream, it is possible to implement numerous beneficial solutions to many industries, and AEC is one of them.

According to the report from 2017 about emerging technologies on Gartner's Hype Cycle, VR was leading on the Slope of Enlightenment pivotal phase. In other words, many industries started to understand the benefits and concepts of technology and how it could help them, while multiple generations of VR products came to the market. [123], [124] Immersive technologies have also been considered one of the top 10 strategic technology trends for 2018. [125] Gartner's Hype Cycle consists of five consecutive key stages, Innovation Trigger, Peak of

Inflated Expectations, Trough of Disillusionment, Slope of Enlightenment, and Plateau of Productivity. [126]

As of today (December 2020), VR devices are more accessible for everyone, and for example, HMD Oculus Quest 2, the newest development, can be bought for €349 as a standalone device [127]. VR technology is currently recognized as a more mature and mainstream development (Plateau of Productivity). [128] Based on the historical background, immersive technologies have been implemented in many industries due to their innovative nature, allowing users to visualize the virtual world as if they were standing next to the objects, interacting with these elements, and experiencing the display with all senses. The development has come a long way since its first principles were seen in The Wheatstone mirror stereoscope prototype in 1838. The early concepts helped to form what is known today as Virtual Reality.

Subsequent subchapters refer to benefits, software and simulation components, and types of VR. Various examples of applications for the AEC/FM industry are presented later in the report. (3.4.1.5. VR applications for the AEC industry).

3.4.1.2. Benefits of using VR

When comparing traditional presentation methods to VR capabilities, few distinctive differences can be highlighted. The conventional approach refers to static display with the support of drawings, models, and videos, and architectural walkthroughs, for instance, to communicate design proposals to the client. [50] [56] On the other hand, VR solutions offer more dynamic presentation techniques – emphasizing user-experience and interactive communication with virtual representation. [59] Users in a Virtual Reality Environment can experience and explore presented information and models in a visual manner as if they were next to displayed objects. [54], [40]

VR technology can be implemented already in the early conceptual design phases to solve various issues connected to a high degree of abstraction, planning, and ideas built in the development. [60] It can be understood as building up complex and hypothetical solutions that can be communicated and explored before making certain decisions.

3.4.1.3. VR software and simulation components

Kieferle & Wossner [59] proposed seven rules on using VR in the AEC industry to maximize the potential of immersive technology. At the time of the study, VR was a relatively new technology on the market. The guidelines were constructed on the claim that VR can display much more than what can be seen in the real world. The first rule advises forgetting reality limitations and forces such as gravity or proper scale. If VR does not require reconstruction of the same environment, designers and users should not build unnecessary barriers. The other steps refer to materializing and **presenting thought process** for communication with symbols of connecting ideas; **visual display of properties** to their objects (wind speed, tensions, and forces, time to real-time simulations); **using as many senses as possible** for complete impression; providing **interactions with objects and other users** to aid more immersive feelings and collaboration; **adding animation** to the VR experience, and final rules address **creating a working environment for team members**. [59]

Researchers [54] gathered essential elements in their study that needed to be considered when making a Virtual Reality program. It includes **3D scene loaders** constructed from one or more files with data consisting of geometry, positions, and textures, among others, necessary for structuring the VR environment. Moreover, it consists of **navigation mechanisms** (moving ability for users – for instance, freely movement or with predefined routes in the created system); **collision handling** (restrictions, with possible activities such as opening a door); **dynamic object animations** (can be created and exported with software Autodesk 3Ds Max or Maya); **physics simulation** (water, gravity); **characters interface** (artificial intelligence for more advanced behaviors of characters or objects put in the virtual world); **spatial sound** (essential for even more realistic immersion in VR world); and **human-computer interface** (what could be used for movement - mouse, keyboard, game controllers). [54]

3.4.1.4. VR types

Three stages can be highlighted for Virtual Reality experience:

- **Passive** (little control over the displayed environment, a user can listen, see and feel – for instance, a compulsory fly-through);
- **Exploratory** (a user can investigate the environment, moving around experience such as architectural walk-throughs);
- **Interactive** (on top of exploring feature, VR enables users to interact, move or even change the objects – for example, opening a cupboard or modifying colors. [129]

VR and connected approaches to the technology can also be divided into five categories following the research of Getuli et al. [8]: Desktop-Based VR, Immersive VR, 3D Game-Based VR, BIM-Enabled VR, and Augmented reality.

- ➢ **Desktop-Based VR –** the 3D virtual environment is displayed on the desktop screen and does not need any equipment (HDM, tracking devices) for investigating the models. Instead, the mouse and keyboard are used for movement and interactions.
- ➢ **Immersive VR –** specialistic equipment is necessary, HDM, and sensor joysticks. This type provided its users with an interactive and immersive experience.
- ➢ **3D Game-Based VR –** is established with the support of a game engine; it refers to serious gaming and simulations built-in programs such as Unity3D. Video-game format is combined with interactive VR solution with the possibility of a multi-player feature. (See Chapter 3.3 about Digital game)
- ➢ **BIM-Enabled VR –** The data provided in BIM models are transferred together with geometry to VR solutions. A building's design can be investigated entirely with information about components, construction processes, and more. (See Chapter 3.2 about Building Information Modelling)
- ➢ **Augmented reality –** the view of the real environment is being combined with virtual data. AR technology is explained more in further chapter 3.4.3 Augmented Reality.

VR systems can also be categorized based on their **immersive character** – intuitive, engaging, sense of presence. Depending on how much the VR environment participants are able to experience, VR can be extinguished as **semi-immersive** (only parts of the immersive character are present) or **fully immersive** (users interact with full-scale portray of the real entity). [40], [130], [11]

3.4.1.5. VR applications for the AEC industry

VR is found in various applications to support the work of the professionals in the AEC industry. The immersive technology can be adapted not only to reconstruct real environments but also to form conceptual ideas in the design and create new architectural spaces outside the limits of the standard imagination. [60] Moreover, VR is closely connected to BIM in this project research. In most of the literature review examples, a building information model acts as a starting point of any VR prototype.

VR can supply BIM models with another dimension of experiencing the digital representations of buildings and collaboration between participants of projects. [42]

The below table shows an overview of selected VR applications in the AEC industry based on the literature study. It follows trends and proposed solutions to different problematic statements in chronological order of the issue date.

VR applications in the AEC industry – a literature study			
Reference	**Problematic statement**	**Solution**	**Conclusion**
Seven rules for a new approach of using immersive virtual reality in architecture **[59]**	Investigation how VR via CAVE environment can be applied as an informative approach on top of visual presentation	The study sets seven rules and tests them to create immersive VR combined with invisible information. The study extends the traditional expression of architecture.	Rules: Forget reality limitation, show thought process, give visible meaning/properties, using many senses, supply interaction, add animation, collaboration
Industrial applications of virtual reality in architecture and construction **[131]**	Patterns are explored regarding using VR in the construction industry and what strategies are there behind applications	Reviewing different applications – VR for new markets, design review, showing technical competencies, interactions with models.	VR is applied in the companies that work directly with customers
Virtual prototyping to design better corporate buildings **[132]**	2D static representations (computer screen, paper) not enough to fulfill future needs and human behaviors.	Social Architecture – uses VR to present different states of organizations and future changes.	VR is an interactive mechanism to simulate the world in 3D and 4D time, decision-making tools in the design process.
User participation in the building process **[57]**	Constructing ICT-based methodology for including end-users in the design process.	Virtual Innovation in Construction methodology proposed, consisting of contextual inquiry, conceptual modeling space, functional consolidation, solution space. It was tested on three projects.	VR environments provided collaborative solution space. End-users help in understanding the needs and revise them during the design process.
Integrating BIM and gaming for real-time interactive architectural visualization **[47]**	Addressing interoperability for the BIM game prototype with a game engine and	A framework is created with user interaction in the architectural process and evaluation. It is	BIM is encouraged to be used with gaming solutions for educators, architects, and engineers

	showing advantages of VR gaming integration in the early design stages	supplied by a scenario of following paths in the models to check accessibility.	to create walk-through scenarios.
Virtual reality-based cloud BIM platform for integrated AEC projects **[7]**	Searching for innovative solutions for unified collaboration between teams in AEC to coordinate tasks, design methods, and delivery processes. VR BIM cloud platform is proposed.	The study navigates throughout the creation of new relationship models for collaboration with gaming interfaces and understanding of the Integrated Project Delivery concept. Decision-making for design is encouraged. Quest3D was used for VR programming.	Still, in the early stages of development, a cloud-based simulator helped trainees learn about risks and concerns before the work is done in real-life. It is possible to go through various scenarios that could happen on the construction site.
Virtual reality as an empirical research tool – exploring user experience in a real building and a corresponding virtual model **[133]**	Investigating the potential of VR for human-environment relations research and user experience. A qualitative and quantitative study.	The virtual model was used in World Viz Vizard 4.0; both predefined walkthroughs and the user's a free movement with a gamepad.	Test of VR experience in comparison to the same real space. VR has capabilities for empirical, psychological, and architectural research
To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning **[134]**	Investigation of VR for training, teaching, research for architecture, landscape and planning of environments	Design and Visualization System proposed with walkthroughs simulation and impact assessment in VR; cameras, controllers, and sensors applied.	Challenges and opportunities are listed for each discipline. A retrospective user's feedback solution and interactive management of the models and pictures are highlighted
BIM-based collaborative and interactive design process using a computer game engine for general end-users **[50]**	There are only a few practices that could potentially supply designers with tools to increase productive interactions for collaboration with clients and end-users.	Most technological solutions from BIM and FM focus primarily on design, construction, and maintenance processes. The integrated data exchange in a created BIM and VR system is eased with a game engine collaboration add-in between Autodesk Revit-Unity3D.	Multiple users can make modifications to the design through the connected network from the developed prototype. It provides a method to involve end-users actively in the design development to assess the building's requirements
Safety by design: dialogues between designers and builders using virtual reality **[135]**	Designers need input about safety hazards on the construction site to investigate their design solutions.	VR capabilities were examined for collaboration between architects and constructors to enable safety measure learning. Participants tested the VR system with construction and design scenarios.	Designers can get positive learning outcomes on safety design when collaborating with experienced constructors. It also allows architects to adapt details instead of changing entire aesthetic factors.
Development of a Virtual Reality Solution for End User Involvement in Interior Design **[56]**	Testing a VR solution based on identified users' needs and functional requirements. The proposed solution	The system prototype was tested in hospital design (room layout) for user involvement with VR experience using	The findings suggest that there is potential to use VR systems for end-user involvement. VR provided spatial

	could replace physical mock-ups of buildings for user investigation of design.	Oculus Rift, touch screen, and Unity game engine for the prototype development. Users were able to change room area and move equipment in the model.	understanding. It was found problematic to interact with objects on the touch screen but the study indicates promising outcomes for integrating users in interior design.
Conceptual BIM modeling in immersive virtual reality **[60]**	Finding a balance between abstract ideas, functional solutions, and understanding with a client.	VR experience created with BIM modeling platforms – ArchiCAD, Trimble, Revit; Game engine and animations: Unity 3D, Visual Studio 2015, 3Ds Max Concept Information Model	VR for research and education; solving real-time conceptual design tasks; decision-making in BIM model during initial design stages; the study addresses Level of development 0-100 gap.
Collaborative design model review in the AEC industry **[54]**	Exploring VR capabilities for running and reviewing meetings in the AEC industry by different professionals to lower the loss of money and time.	An application is introduced based on available tools and tested with a case study.	VR is shown to be effective with visualizing feedback, to increase the efficiency of design and planning, meeting clients' expectations, improving workflow and collaboration, and breaking down geographical barriers in the project teams.
Integrating Virtual Reality and BIM for End-users Involvement in Building Design: A Case Study **[58]**	Investigation of VR and BIM potential to involve end-users actively in the design process. The case study addresses the traditional practices of handing most responsibility to architects regarding decision-making.	The case study was about furnishing some rooms in a university building with the implementation of an integrated VR and BIM system to involve end-users in the process.	The future users of the building felt more attached to the workplace and were found of the technological solution. There was a reduction of time that would normally be required for the creation of the alternative proposals.
Simulation and Serious Game for Fire Evacuation Training **[9]**	Fire safety issues in complex buildings, finding fast escape routes, ineffective fire drills – a high number of deaths in building's fire in Europe.	BIM model with a high level of detail for visual elements imported to the game developing platform. Set up with the first-person point of view, use of the screen, mouse, and keyboard; without VR headset.	Escape situation training VR with SSG - simulation and serious game (different scenarios and 4 levels of difficulty); it provides promising test results.
Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study **[136]**	Visualization on screens does not provide a highly immersive experience and most of the meetings in AEC require physical presence.	The authors teamed up with software providers for investigating collaboration capabilities in the VR system integrated with BIM.	Diverse professionals in AEC found it beneficial to work with VR. The study introduced a simulation with clash detection, on-site tasks performance, remote collaboration, and design review.
A project framework to introduce Virtual Reality in construction health and safety **[8]**	The high rate of injuries on the construction site.	Framework on use of BIM model with VR immersive environment	A VR system for personnel supports Health and Safety before

	Needs for more preventive measures.	to guide training, collaboration, and site design approval	they start the work. Sound and interaction scripting was added.
Rapid 3D Reconstruction of indoor environments to generate virtual reality serious games scenarios **[137]**	Producing a VR environment with a realistic user experience and added storylines can be a time-consuming process. Investigation of different methods of implementing VR for serious gaming.	Methods of reconstruction are compared with a case study - earthquake evacuation. (Building up a BIM model, using laser scanning and 360-degree panorama cameras)	Both laser scanning and 360-degree panorama can provide a more realistic VR experience and faster to construct. However, BIM models give more dynamic capabilities to interact with the objects.
Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation **[90]**	Identification of issues and challenges concerning 4D simulations in the VR environment.	Evaluation with a case study; steps of the transition of 4D simulation from Navisworks into the VR – different data exchange (Revit-Navisworks-3Ds Max), adding MS project timeline, and then placing the file in Unity 3D game engine	A proposed framework supports constructability analysis meetings. 4D simulation in VR offers not only walkthrough-centered analysis but also the use of timeline abilities. Need for better data exchange between software.
Interactive virtual reality tool for BIM-based on IFC – Development of Open BIM and Game Engine based layout planning tool – a novel concept to integrate BIM and VR with bi-directional data exchange **[42]**	Lack of complete IFC format exchange for BIM and VR integration. Models striped out of information when sent from the VR platform back to BIM.	During the case study, 3D BIM data models were reviewed for VR. Unity game engine and xBIM program were used to set up IFC_VRXML format file and prepare models; Two-directional exchange.	The designed solution allowed to be used as a space planning and design interaction tool with changes synchronization to the original source. Need for more development.
Virtual reality in architecture, engineering and construction industry: proposal of an interactive collaboration application **[92]**	The process of BIM solutions contains some limitations in extensive use because of complexity. A better understanding of virtual models is searched.	A game engine was incorporated to provide an interactive collaboration application with an intuitive user interface based on BIM and VR technologies.	VR allows a comprehensive and effective understanding of digital models before the buildings are constructed. It enables stakeholders of a project to interact and assess design solutions in a collaborative VR solution.
Immersive virtual reality serious games for evacuation training and research: A systematic literature review **[138]**	Investigation for improving emergency measures in case of fire and earthquake – addressing the potential of VR and Serious Gaming for training.	The paper provides a literature review for VR and Serious Gaming and highlights the potential for engagement and learning by the users.	The developed framework included a critical assessment for the effective development and implementation of these technological solutions that can improve emergency behaviors.
Virtual Reality use for Evaluation and Improvement of Building Emergency Signage **[139]**	Use of VR for an emergency – to improve buildings' signage	40 Users tested the experiment with HDM and assessed the prototype in a facility for emergency simulation	VR is an effective means for the evaluation of emergency scenarios to improve signage. It can allow the assessment of users' behavior in the

			event of stressful emergencies.
Evaluating immersive and non-immersive VR for spatial understanding in undergraduate construction education **[140]**	Pedagogical importance investigation of VR for teaching construction students for design assessment.	The desktop viewer and HMD were compared concerning learning by 32 students. They were tasked to find intentional mistakes.	HMD users performed to some degree better than desktop viewers, but observations indicate that knowledge, navigation habits, and technological experience can alter how they see the design.
Design and Development of a Virtual Reality Educational Game for Architectural and Construction Reviews **[5]**	VR educational game for supporting evaluation and review of BIM-based design by students in AEC. The statement answers the growing adoption of BIM modeling platforms that needs more innovative learning interventions.	Design Review Simulator was developed as a VR serious simulation game. Students could investigate mistakes in construction projects via VR. The instructional framework was completed: "*analyze, design, develop, implement and evaluate".* Unity 3D is used for the development of the game.	VR and educational games are recognized for their abilities to enhance learning in classrooms, high levels of engagement and motivation. However, there is still unutilized potential for students learning in design and construction disciplines.
Real-time Evaluation of Room Acoustics using IFC-based Virtual Reality and Auralization Engines **[141]**	The study report presents VR use with Auralization, an uncommon practice to add sound and acoustics for the indoor environment to visual features	Acoustic performance is assessed with VR to provide process, results, and user framework information for the development of VR with the Auralization system. Hardware used during the testing includes Oculus Rift, Quest, HTC VIVE, and CAVE using Epiito programs.	Such development has a promising potential for stakeholders' improved decision-making during design phases and as a cost-effective solution. Including room acoustics evaluation with the VR system enables non-specialists' users (clients, end-users) to understand and experience different design outcomes.
Virtual Reality based Facilities Management planning **[142]**	Examination of VR usability for Facilities Management (FM) planning as FM, BIM, and VR receive recently growing adaptation spotlight in the AEC industry.	Both quantitative (rating experience in VR) and qualitative (interviews) research was conducted for assessment of VR for Facilities Management.	VR is found (82%) as a suitable planning tool for Facility Management.
Developing building information modeling based virtual reality and mixed reality environments for architectural design and improving user interactions with serious games **[143]**	The study aims to enhance user experience and interactions with serious games that are based on BIM, VR, and MX solutions.	An architectural design and visualization tool are constructed for VR, MR, BIM, and serious gaming integration to enable user experience and interaction. The created program is tested by designers and game providers.	The designing tool and game prototypes were perceived positively for use in BIM models integrated for VR and MR worlds that allow improvement in the design workflows and user's experience.
Becoming familiar: how infrastructure engineers begin	Because of the growing interest in VR, the big-	3D-MOVE VR system is proposed for VR	The VR environments based on 3D- MOVE VR

to use collaborative virtual reality in their interdisciplinary practice **[144]**	scale VR environment is investigated and how it could be implemented for professional work in project review.	collaborative work and examined in the real construction firm.	and CAVE can provide for the user's collaborative engagement, reflections, and feedback, discussions about design solutions and social aspects improvements
A framework of procedural considerations for implementing virtual reality in design review **[40]**	There are still procedural challenges for the effective implementation of VR in communication and assessment of the design.	7 interviews with stakeholders were conducted for the practicality of VR in the real project case (a new school). Steps considerations are examined for feedback acquisition in the VR design review.	The study and proposed framework provide the foundation to focus on practical indication connected to VR-based design reviews and user's involvement in the process (clients, future occupants).
From BIM to extended reality in the AEC industry **[145]**	Challenge in interoperability and data translation from design to construction, and operation and maintenance	Utilizing BIM and XR together for the improvement of AEC projects, incl. time, cost, quality, and safety.	The research could serve as a basis to close the gap of technology acceptance and to promote a technology-oriented industry.
User Elicited Hand Gestures for VR-based Navigation of Architectural Designs **[146]**	Proposal of using hand gestures instead of a physical controller for the VR navigation by designers and architects.	The gesture proposal was assessed with usability, intuitive, and ease aspects.	The findings indicate that the designed gesture system is productive.
An Immersive Virtual Reality Serious Game to Enhance Earthquake Behavioural Responses and Post-earthquake Evacuation Preparedness in Buildings **[78]**	The decreasing number of casualties, improving procedures in case of earthquake emergency and preparing users with VR and Serious Gaming.	Immersive VR and Serious Gaming are used to avoid limitations from traditional methods (seminars, videos, or emergency drills) for evacuation training. A system was proposed to improve users' behaviors and tested with the hospital case study.	The findings suggest that the system resulted in improved knowledge and self-efficacy of participants (hospital personnel and visitors). The users found it easy and captivating to participate and learn with VR and Serious Gaming the most effective evacuation procedures.

Table 3 - VR applications in the AEC industry

3.4.1.6. Virtual Reality Sickness

VR is described as a technology that induces specific behavior in an organism through the use of artificial sensory stimuli, while the organism has little to no knowledge of the intervention. There is no external force in VR that affects vestibular stimulus, and there should be at least one visual motion control system that results in concordant visual and vestibular information. [147] [148]

A critical element of Virtual Reality is that the person wearing the headset should not experience any VR nausea. This sickness is primarily triggered by the sensory discrepancy between the perception of self-motion and the vestibular system, together with achieving a comfortable frame rate. [149] The virtual environment must respond correctly to the movement of the user to prevent the user from getting ill. For example, if the person moves his head to the left, the avatar's camera from the virtual world moves to the left as soon as possible. In the program, the user needs to be able to move through various rooms to test the space. To be able to move in the virtual environment, the user can use the controller from Oculus or any other VR headset to click on a direction and move towards it, but this form of action triggers VR sickness because the person is stable while the avatar is running. [150]

Other symptoms of VR sickness include apathy, discomfort, drowsiness, disorientation, eye strain, fatigue, and the factors creating this condition have been studied by researchers which include: duration of VR exposure, age of the user, gender, illness, field of view, usage of VR standing/seating, active/passive. [151] [152]

3.4.1.7. Data Tracking for Virtual Reality

Virtual Reality has the benefit of setting up a well-controlled experience while also allowing the participant freedom of movement and presenting it in a reasonably realistic world. The person can look in both directions by turning his head, almost like in the real world. Simultaneous to the head's rotation, the orientation of the stimulus concerning the position of the subject may be determined with high accuracy. A high immersion of the subject with the virtual environment can be accomplished by coordinating the body motions and images presented to the eyes. By supplying the senses with the knowledge of this environment, participants acquire a sense of identity in the non-physical world [153] [154].

VR experiences for architecture purposes can use the head orientation/rotation of the test person to create a heat map of the most attention areas. Head orientation is the standard way to catch the user's vision - that is where they're looking. In VR, a raycasting feature fires a virtual laser beam from the middle of the user's focus until it reaches the closest virtual object. The target shows the item most likely to be seen by the user. This is very helpful because understanding the person's location alone is not enough to explain how they communicate with the VR world thoroughly. [155] [156]

Technologies such as virtual reality and eye-tracking have been considered in the past years but specifically for research purposes. VR, firstly used for the exhibition of the current architecture, is not finding its place in the design process. Client-based design is one of the techniques that benefit significantly from the use of VR technology. [156] Compared to classical eye-tracking, VR eye-tracking is a reasonably modern and promising innovation with its first appearance in literature at the beginning of this century. [157] It opens up a variety of new opportunities for studies on human cognition and behavior. It provides researchers with tools that were previously unavailable.

Eye-tracking in virtual reality contains many parts to set up before you start. It consists of different hardware and software components, such as:

- **VR-Hardware set**, which must include the head-mounted display, controllers for the virtual world, and motion trackers. (Oculus, HTC)
- **Software** needed to create a virtual environment such as Unity, Unreal Engine, or Vizard.
- **Computer hardware.** It is crucial to run the virtual environment at a high frame rate, as reaction lags and jittery gestures can easily lead to motion sickness in the test

persons. The computer is usually used as an interface between the eye tracker and the VR hardware as well as to capture all data on the actions of the subject.

- **Eye-tracking sensor** to capture the data from the test subject
- **Headphones** will reduce the surrounding sounds making a more realistic experience.
- **Cable Management** in case of older versions of HMDs, for preventing users to tangle around the cables. [155]

While using eye-tracking technology, it is possible to know where the person is looking accurately, and not only the head's direction. For example, signage in the building might be wrongly placed or hard to see. Therefore more seconds spend in that specific direction can be tracked and thus taken into account. But the most important application of eye tracking in VR is the rendering of the scene. While in VR, there is a lot of demand from the GPU, resulting in low resolution and less accuracy of the environment. Eye-tracking in VR is trying to follow the human eye focalization, to render only the objects the person is looking at currently, reducing the resolution on less visible objects.

Another way of capturing data that follows almost the same setup explained above is through position tracking. It helps researchers to estimate the adequacy of a room to its purpose. The importance of monitoring systems in busy environments, such as hospitals, airports, universities, is well known; the effects of such systems are less clear before they are made more explicit. For example, the impact of an insufficient emergency route can be horrific, even on a smaller scale than hospitals or universities. [158]

The most important information you can get from a VR experience is the accurate 3D coordinates (x, y, z) of the user at any given time during the session. The VR headset is the center of all tracking for positioning the user's virtual body in VR. These coordinates are a three-dimensional vector representing the actual location of the user's head in a 3D plane in the X, Y, and Z axes. [159] This way, by using coordination tracking inside an immersive reality with end-users, different escape paths can be tested and the accessibility of the building.

There are also other tracking technologies for VR, such as hand-tracking, body movement tracking, voice capture, multiuser-tracking, action tracking.

3.4.2. Mixed Reality

Mixed reality varies in the spectrum between a real and virtual world that consists of entities of both classes merged into one display. In other words, Mixed Reality is limited to two borders – Real and Virtual Environments. [2]

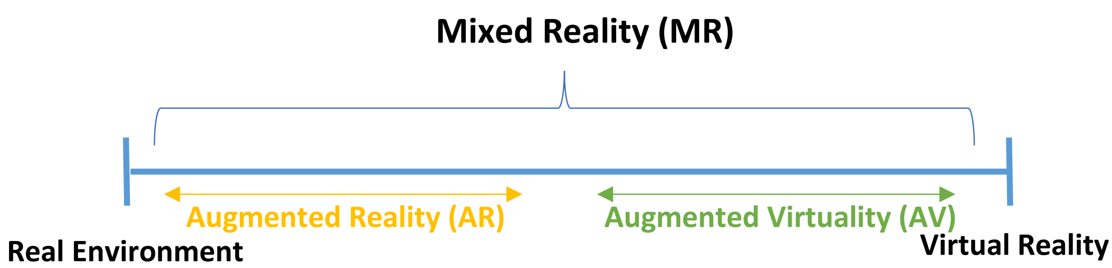


Figure 7 - Explanatory figure of Extended Reality terminologies, based on the Reality-Virtuality Continuum [160]

Figure 7 presents the range of Mixed Reality in the defined continuum by Milgram & Colquhoun [160] - *The Reality-Virtuality Continuum*. It shows the parallel nature of the two approaches with the different concepts the Mixed Reality technology includes. The most important differences and similarities between the various terms can be extinguished.

A virtual Environment does not consist of any real physical elements in the displayed world but is entirely modeled to be rendered. On the other hand, Real Environment is the unmodelled representation of the actual space. [160] Milgram & Colquhoun also bring a defined spot of Augmented Reality on the spectrum. AR can be described as an environment where virtual elements are added onto the real scene, as opposed to Augmented Virtuality, where real objects are put into virtually created space.

3.4.3 Augmented Reality

Augmented Reality (AR) is another immersive technology next to VR applied in the AEC industry to enhance opportunities and innovations, essential for workflow improvements, especially concerning the construction sector. [161] AR can be defined as part of the Mixed-Reality continuum that uses a combination of real-world scenes with virtually generated entities by computers. Some researchers initially have narrowed AR down to systems using either head-mounted or head-up displays. Others also defined AR as systems that incorporate giant screens for presenting augmented realities. [160]

Other sources add to the definitions that the digitally modeled details can be expressed as images, text, and animation on top of the real-world and viewed and experienced on any available technological means – smartphones, headset, tablets. [100]

The construction industry is the main domain in the AEC that could benefit from Augmented Reality's implementation with its overlapping virtual entities in a real environment. The AR technology can enhance complete BIM implementation in companies to bring a wide range of advantages for these firms – it can provide real-time visualization of projects, for instance, viewing BIM model on top of the already built parts of buildings. It further leads to improved collaboration and communication between team members, a better overall understanding of the executed tasks, and more effective decision making. AR can bring to the construction projects the other potential benefits of reducing project duration and costs, waste minimalization, better health, and safety with the training possibilities. [162], [161]

Dunston & Shin [2] extinguished application areas in the construction where AR could bring the most positive outcomes and disregarded sectors where it would not be needed. The highlighted work tasks that could be improved with AR implementation consist of: preparing site layout, excavation, positioning (orientation and locating the desired points), inspection, supervision, coordination (organization of workflows or resource), commenting, and strategizing (includes detailed steps for each activity).

Dalux is an example of an AR tool that is compatible with different BIM platforms (Autodesk Revit, Navisworks, Graphisoft ArchiCAD) through the use of the neutral-based file format – IFC. The company has worked since 2005 to improve the construction industry's processes. The software components (BIM Viewer, Dalux Box for designing, Dalux Field – for construction, and DaluxFM for facility management) allow collaboration between different professions, interactions in the immersive environments, and share models, plans, and related documentation. Users without prior knowledge (clients, end-users) can easily open on their mobile phones free BIM viewer with given access to associated projects. [163] For another example of AR development, Morpholio Unveils AR Sketchwalk can be highlighted, a program that enables supportive work for architects to close the gap between Virtuality and Reality. For instance, a tablet can be used to position digital 3D sketches onto real surfaces where the users can walk with the device. [164], [165] It is also possible to create own application for the construction industry with the proposed framework by [161], where the researchers completed the experiment and questionnaire with the users. The 3D model file was sent with location and scale information to the Hoppala AR website and then converted with LayAR for the immersive experience to use the virtual model on top of the real environment construction site.

The conducted survey gave an overview of how AR is perceived in terms of effectiveness and its most applicable purposes. The findings suggest that AR can support diverse activities concerning the construction industry, with design and tasks in building execution getting the most votes for most applications. [161]

The table below provides an overview of AR solutions in the AEC based on publications.

AR applications in the AEC industry – a literature study			
Reference	**Problematic statement**	**Solution**	**Conclusion**
Mixed Reality-Based Visualization Interfaces for Architecture, Engineering, and Construction Industry **[166]**	Investigating how Mixed Reality technologies (especially AR) can be integrated for the AEC industry.	Milgram's taxonomy and Reality-Virtuality continuum addressed for helping with system specification. AR-CAD prototype was proposed for the study of human interaction with 3D Virtual models.	Human aspects are important to consider when interacting with the Mixed Reality interface. The technology can help with tasks such as design review.
Identification of application areas for Augmented Reality in industrial construction based on technology suitability **[2]**	Identifying suitable AR application in the construction industry	The goal aims to provide a comprehensive map with AR applications. The task-technology fit process was determined.	AR for site layout design, positioning, supervision, inspection, strategizing, commenting, coordination, and excavation
A conceptual framework for integrating building information modeling with augmented reality **[167]**	Addressing how BIM's design process can be integrated with AR for communication on-site.	A conceptual framework is proposed for such integration.	The findings indicate for AR to be effective in the construction industry, it needs to be supplied with tracking and sensing tools (RFID – radio frequency identification, laser marking, and movement tracking)
Integrating End-Users in Early Ideation and Prototyping: Lessons from an Experience in Augmenting Physical Objects **[168]**	Designers and End-Users in distorted conceptualization may feel demotivated and discouraged when they are not familiar with the	Two tools are proposed to be used for supporting early design and conceptualization with AR: CoDICE and ECCE.	Three features were valued during the study by its users: following process flow, investigation of numerous concepts with

	purpose of the different design activities.		interaction, and building up own prototypes
A Framework for cloud-based Virtual and Augmented Reality using real-time information for construction progress monitoring **[169]**	There is a limitation to the more widespread application of AR in construction progress monitoring as the BIM program is usually not kept up-to-date between office and construction site.	An integrated cloud framework is designed to keep track of construction progress in real-time with both ways of data exchange. New opportunities are investigated with new devices for VR/AR and their potential in the industry.	The construction monitoring and data exchange process are based on passive data collection, use of immersive equipment, and cloud system. The study elaborates on the foundation for the development of prototypes for collaboration in the industry.
The application of Augmented Reality (AR) in the Architecture, Engineering, and Construction (AEC) industry **[161]**	Investigation of available AR concepts with benefits and limitations in AEC.	Experiment and questionnaire; 3D model file, location, and scale data sent to Hoppala AR website and then processed to LayAR.	AR is suitable in the construction industry for diverse activities, especially design and inspection.
A review on Using Opportunities of Augmented Reality and Virtual Reality in Construction Project Management **[170]**	A comprehensive critical review of AR and VR in construction management is absent in the literature.	The study completes the summary review for potential AR/VR opportunities to solve construction management issues.	Application for visualization, defect and quality management, safety management, training, communication, and data acquisition
A critical review of the use of Virtual Reality in Construction Engineering Education and Training **[171]**	VR and AR applications are reviewed for construction, engineering, education, training, design, visualization, health and safety practice, machinery and operational activities, structural analyses.	The three-part examination is conducted - VR and AR technology, applications, and future developments. Information is gathered from various publications between 1977-2017.	VR adaptations are changing over the years: from desktop viewer VR, interactive environment, 3D game simulation to integrated BIM and VR/AR solutions. The study provides scope for implementing an immersive solution for training courses.
Quality assurance and process control in virtual reality **[172]**	Finding suitable measures for manufacturing with a low tolerance for errors, and remote automation with monitoring production	A *"man in the loop system"* assessment in VR; 3D simulation of the robot cell	VR and AR to support humans with the inspection process, to see invisible data, remote assessment, automated processes in quality assurance
BIM, Augmented and Virtual Reality empowering Lean Construction Management: a project simulation game **[46]**	Finding how BIM with AR/VR can support Lean Construction throughout the project's processes.	Simulation game Villego for project management, tested by a group of students. Traditional methods (critical Path Method, Gantt Chart, drawings compared with technological means of Industry 4.0 (VR, AR, BIM)	The collaboration processes with technological solutions (especially AR to build physical models) were more productive and faster with less waste of the building blocks.
End-Users; Augmented Reality Utilization for Architectural Design Review [173]	Ensuring that the AR system is effective from the perspective of the end-users to include them in the design	Three types of the 3D model display were implemented in the research to be tested: 2D desktop view, VR, and	The findings suggest that AR application is effective and sufficient for investigating the visual appearance of the

	collaboration. The industry has placed most of the focus on the technological part and not on the user's involvement in the AR application.	AR. Among the criteria for design review, visualization performance, perceived experience, and acceptance were included.	building objects, including user experience, while walking in a virtual model placed in real-life scenery.
Assessing the Impact of a Construction Virtual Reality Game on Design Review Skills of Construction Students [174]	Learning outcomes examination of VR game for design review with critical thinking and collaborative analyses.	One hundred twenty students participated in the investigation of the simulation – one group conducted a design review with 2D drawings, and the other team with a design review simulator.	Students found more mistakes with VR simulation, and the proposed immersive design review enhance gaining more knowledge than just assessment of the drawings.

Table 4 - AR applications in the AEC industry

Stakeholders involved in the design process are essential when using technological solutions; thus, the different actors are evaluated in the next chapter using the interest/power matrix to find the key players who have contact with the end-users/clients and who are responsible for getting the information from them.

3.5. Stakeholders involved in the design process

In this subchapter, a general stakeholder power/interest matrix is shown for the Design stage of a building. A stakeholder is "*an individual, a group, or organization, who may affect or be affected by, or perceive itself to be affected by a decision, activity or outcome of a project*." [175]

The model presented in *Figure 8* consists of a grid in which power and interest are essential variables. Power and interest vary from low to high, and the entities are placed according to a public construction project. Therefore, the ones with higher power and interest in changing the design can be identified. The four different communication strategies are explained below.

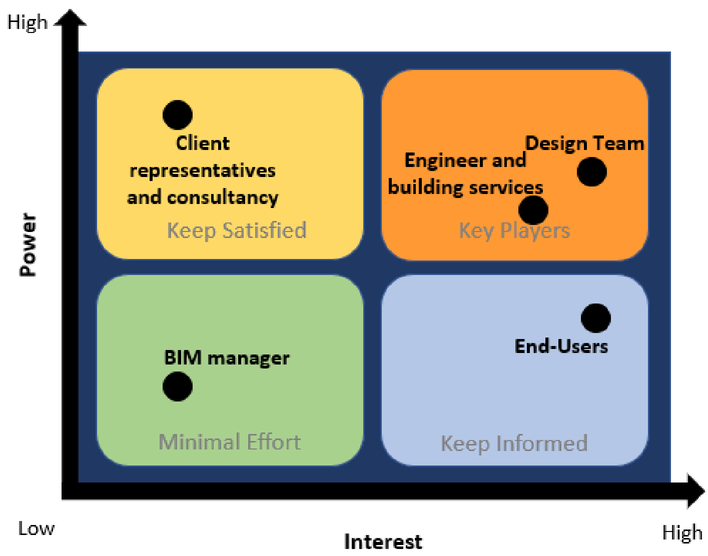


Figure 8 – Power/Interest matrix on the stakeholders in the design phase [176]

- **Key players**
  Stakeholders within this category have a large amount of power and a high interest in the project. These stakeholders need to be fully engaged and must be kept satisfied.
- **Keep Satisfied**
  Stakeholders with high power and low interest. Keep them satisfied but be brief in communication.
- **Keep Informed**
  Stakeholders with low power and a high interest. Adequately inform these stakeholders and communicate to ensure that no major issues are arising. Stakeholders in this category can often be helpful and provide data.
- **Monitor**
  Stakeholders with low power, and low interest. Monitor these groups, but do not bore them with excessive communication. [175] [177]

The Client is the organization paying for the construction project. The owner of the building recruits the consultancy team. The building owner is responsible for the construction project's critical decisions, and, for this reason, the client has the very last word.

The Design team is responsible for the design of the building. This building is intended to be occupied by the users, which is why the design team must consider the flow, the look, and the environment of the building.

Engineer and building services are responsible for designing the technological elements of the construction, such as calculations and solutions based on the building's structural principles and energy usage, as well as all the services necessary for the functionality of the building.

BIM Manager is responsible for project coordination and communication, efficient workflow, and 3D modeling. His team conducts all the BIM procedures.

End-users. The users may also be referred to as an end-user, which means that the "end" is the completion of a building, i.e., when it will be used for its intended purpose. The end-users must communicate their requirements to the design team. This knowledge aims to ensure the construction of a building that fulfills the daily tasks run by the users. [178] [175]

In the following sub-chapter, the literature review will be summarized in a table to understand better the essential parts researched in this report.

3.6. Overview

Table 5 presents the essential points from the literature review. These outputs are used as supplementary views to interpret and analyze the data collected from the semi-structured interviews, later in this report. Takeaway statements are categorized by the related topic they refer to.

Re-visiting important takeaways from the literature review

User involvement enhances increased assessment of functionality, usability, consistency of requirements, and efficiency of product development	[19]	**End-users / Client involvement**
The end-users may feel more connected to the building they will occupy in the future. Thus, their involvement in the design stage can act as incentives for future users	[33]	**End-users / Client involvement**
It is not a common practice to involve the end-users before they start occupying the building unless the clients are also the intended future users of the building.	[35]	**End-users / Client involvement**
It is challenging to include end-users, though in all projects and receives reflecting input they would have in the future building.	[30]	**End-users / Client involvement**
Types of end-users depend on what project it is. Hospitals, universities, office buildings – each facility have different intended use. Therefore, every project needs special considerations by designing them	[36]	**End-users / Client involvement**
The varying backgrounds of end-users can lead to conflicting views on the needs and expectations of a building they are about to occupy regularly, visit, live, or work in. They hold necessary insights into the usability and functionality of a building.	[57]	**End-users / Client involvement**
The physical environment influences the end-users' productivity and happiness – if a building is not designed following their true needs, it affects how they perform their duties.	[37]	**End-users / Client involvement**
The requirements for the design review application should include and examine the functionality, accessibility, safety, and effectiveness of the spaces in the buildings for the future occupants.	[40]	**End-users / Client involvement**
The involvement of clients and end-users could bring more effective and efficient results if they were to be included more actively in the process	[50]	**End-users / Client involvement**
When future users are involved in the designing process**,** they feel more attached to the workplace.	[58]	**End-users / Client involvement**
BIM models and VR experience can support the understanding of building projects through careful planning and making it easier to discover errors and clashes in the early stages of design development.	[54]	**Communication and collaboration**
3D BIM models are found to be more effective for display presentations than the traditional methods of 2D drawings. However, for the designers, only a few practices could enhance productive interactions for working with clients and end-users and to provide functional, active measures.	[57] [50]	**Communication and collaboration**
It is commonly adopted that the design intent is communicated through physical models such as cardboard mock-ups, images from 3D-based software, or even with walk-throughs.	[56]	**Communication and collaboration**
Augmented Reality application (mixed from VR and real-world) is effective and sufficient for investigating the building objects' visual appearance, including user experience while walking in a virtual model placed in the real-life scenery.	[173]	**Communication and collaboration**
Clients usually receive a formal presentation with a static and passive type of information about projects without any interactive form, such as pre-prepared information and models with corresponding views of drawings, displayed on screens or paper.	[50]	**Communication and collaboration**
Improved communication and collaboration between stakeholders and effective assessment for design review may be achieved with VR.	[92]; [136]	**Communication and collaboration**
Involving the end-users in the designing stage can significantly reduce unexpected costs of changes later in the process.	[30]	**Design Changes**
The case study by Ayuba and Adedayo shows that the end-users of public buildings are usually not satisfied with the construction and design choices that caused difficulties with daily operations.	[39]	**Design Changes**
Design changes are inevitable in a construction project and will lead to increased time and costs. Even with the growth of technology use, there are still many design changes.	[17]	**Design Changes**
VR and the development from the gaming industry can provide immersive depth to the BIM models and interactive experience with both first and third-person perspectives	[75]; [76]; [47]	**Virtual Reality**

VR solutions offer more dynamic presentation techniques – emphasizing user-experience and interactive communication with virtual representation.	[59]	**Virtual Reality**
Users in a Virtual Reality Environment can experience and explore presented information and models in a visual manner as if they were next to displayed objects.	[54]	**Virtual Reality**
VR technology can be implemented already in the early conceptual design phases to solve various issues in connection to a high degree of abstraction, planning, and ideas built in the development	[60]	**Virtual Reality**
VR and Serious Gaming scenarios improve the knowledge and self-efficacy of the end-users during evacuation training. It can be applied as a learning method in case of, for example, an earthquake or fire emergency. It can allow the assessment of users' behavior in stressful events.	[78]; [139]	**Virtual Reality**
VR can be used as an interactive mechanism to simulate the world in 3D and 4D time and as a decision-making tool in the design process.	[132]	**Virtual Reality**

Table 5 - Overview of the important takeawauys from the literature review

The information will be used to create the basis for adapting the contextual design of the prototype from Chapter 5. But before going into that, the current state of Virtual reality software used in the AEC industry and Facilities management has to be reviewed to understand better what features and tools are needed to develop a VR prototype.

Chapter 4. Virtual Reality software for the AEC industry

The following chapter will contain a review of the VR tools used in Architecture and Construction, which will serve as a baseline of features and tools needed to create a prototype VR tool for gaining tacit knowledge from the client/end-users in the design stage of a building.

Thanks to the advantages of virtual reality to the market, research initiatives have begun to explore its applications in diverse fields of construction and design. [179] examined the use of Oculus Rift in building safety preparation and worksite management, while [58] assessed the use of Oculus Rift for end-user participation in construction architecture. The improvement in the perception of an apartment has also been examined by [180] using Oculus to customize flats.

Ten known Virtual Reality software in Denmark were chosen for the analysis to create the basis for the prototype design. The programs' investigation contains general descriptions from their website and functionalities of these programs that provide architecture and construction use., The review is conducted by the authors of this report to validate their claims.

This process is focused on the functional features of the different virtual reality software, and as hardware, it was used Oculus Quest and the desktop view. The reviewers evaluated three different functionalities, such as navigation, utility, and simulation, which are tested independently for each software.

Only 8/10 applications were tested with a free trial or a student license. The information for the other two apps has been taken from their website. See Table 6.

The evaluated computer-based VR applications for architecture and construction uses										
Developer	Epiito	Enscape	InsiteVR	Kalloc	Shapespark	IrisVR	The wild	SimLab	Vrex	Revizto
App name	Epiito	Enscape	Resolve	Fuzor	Shapespark	IrisVR	The wild	Composer	Vrex	Revizto
Logo	epiito						THE WILD			revizto
App type	Standalone	Add-on	Standalone	Standalone	Browser	Add-on	Standalone	Standalone	Add-on	Standalone
Use of VR	Purpose	Feature	Purpose	Feature	Feature	Purpose	Purpose	Feature	Feature	Feature
Tested	✓	✓	✓		✓	✓		✓	✓	✓

Table 6 - The evaluated VR applications

Navigation options (*Table 7*) are a vital part of VR's capabilities, as VR's goal in the AEC industry is to provide an immersive experience of the proposed project. These navigation features in VR applications usually include walking, teleporting, scaling, rotating, and adjusting the active camera's height.

Navigation features of the following VR applications										
App	Epiito	Enscape	Resolve	Fuzor	Shapespark	IrisVR	The wild	Composer	Vrex	Revizto
Walk physically	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Walk with button	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Teleport	✓		✓	✓		✓	✓	✓		✓
Adjust User Height	✓		✓	✓	✓	✓	✓	✓	✓	✓
Teleport to view	✓					✓		✓		✓
Rotate view	✓	✓		✓	✓			✓	✓	✓

Table 7 - Navigation features

Most VR software utilizes walking operations in the same way. As both Oculus and HTC headsets are fitted with motion tracking sensors, they can detect the VR user's body movement and convert it into the virtual scene. This movement allows the user to walk in the virtual setting while moving physically in reality. Both VR technologies display a virtual boundary of the physical movement area to prevent the user from colliding with objects in the physical space.

In the virtual scene, the user must visualize the content from his actual height, which can be adjusted accordingly. Teleporting enables the user to immediately travel to every place in the VR scene without walking. This is accomplished by showing the laser beam or projectile signal from controllers to mark a teleport position to the desired location. Besides Shapespark, Enscape, and Vrex, all applications have this feature. Some applications often allow the flying function to go through anything and anywhere in the virtual scene. The apps include displaying a construction model on a tabletop scale as a miniature to allow the user to experience the model from a “god view” to an immersive view. Besides physically wandering around to view the miniature from various angles, most VR apps often allow them to rotate the model with the controllers. Some of them have a scaling function to enable the user to zoom in a specific spot for better information.

Utility features of the following VR applications										
App	Epiito	Enscape	Resolve	Fuzor	Shapespark	IrisVR	The wild	Composer	Vrex	Revizto
Measurement	✓	✓	✓	✓		✓	✓	✓	✓	✓
Markup	✓	✓	✓	✓		✓	✓	✓		✓
Snapshot	✓	✓	✓		✓	✓		✓	✓	
Object information	✓	✓	✓	✓		✓	✓		✓	✓
Track clashes			✓						✓	✓
VR training	✓	✓					✓	✓		✓
Annotations	✓	✓	✓		✓	✓	✓	✓		
Voice recording	✓							✓		
Data import/export	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Synch. To bim model		✓				✓	✓	✓		✓
Landscape design		✓		✓		✓		✓		
IFC import/export	✓	✓	✓	✓		✓	✓	✓	✓	✓
Component library		✓		✓		✓	✓	✓		

Table 8 - Utility features

Although the navigation features are somewhat similar to all ten VR applications, the **utility features** make them distinct from each other in design and construction. VR apps' standard utilities include a measuring tool, a mark-up tool, a screenshot, and a view-saving tool. More advanced utilities that are typically contained only in BIM computer programs include flipping layers on/off, inspecting object detail, and performing segment cutting. *Table 8* outlines the utility capabilities provided by each VR program.

The measuring tool helps the user determine the distance between two points or two objects in the VR scene. This method helps to verify the proportions of the architecture in the simulated project. The mark-up tool helps to apply annotations and notes to the scene for any inspection issues. The snapshot tool comes useful after measuring and marking tools have been used, saving the snap into the design team's model. Most of the applications offer information about the objects in place, giving you an overview of what the model contains, but you cannot change their properties. Tracking clashes feature is developed to quickly identify the clashes and merge them in a report, though only a few apps have this tool, in most of the apps, conflicts can be found and marked up.

Being able to train people within the virtual reality app has become useful for learning how to perform specific tasks or understand the model's functionality. Epiito and Composer offer the voice recording feature - when end-users test the building, they can also leave voice recording notes for particular objects or scenes. The apps allow importing and exporting many different types of files. Usually, the most common ones are permitted by almost all apps, including IFC, FBX, RVT, SketchUp, or Navisworks.

The synchronization with the BIM model is a key feature offered by a small number of apps, and it’s saving a lot of work when the design team is using them. The component library and the landscape design are only used for creating simulations, videos, or renderings of the specific scene.

Although the navigation features make the VR app accessible and utility features make them functional, the **simulation features** (*Table 9*) make the applications stand out for visualization and learning purposes.

Simulation features of the following VR applications										
App	Epiito	Enscape	Resolve	Fuzor	Shapespark	IrisVR	The wild	Composer	Vrex	Revizto
Move objects	✓	✓		✓			✓	✓		
Material change	✓	✓		✓	✓		✓	✓	✓	✓
Object interaction	✓			✓			✓	✓	✓	
Light simulation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sound simulation	✓	✓		✓		✓		✓		
Fire simulation				✓				✓		
Animation simulation							✓	✓		
Multi-player	✓		✓	✓		✓	✓	✓	✓	✓

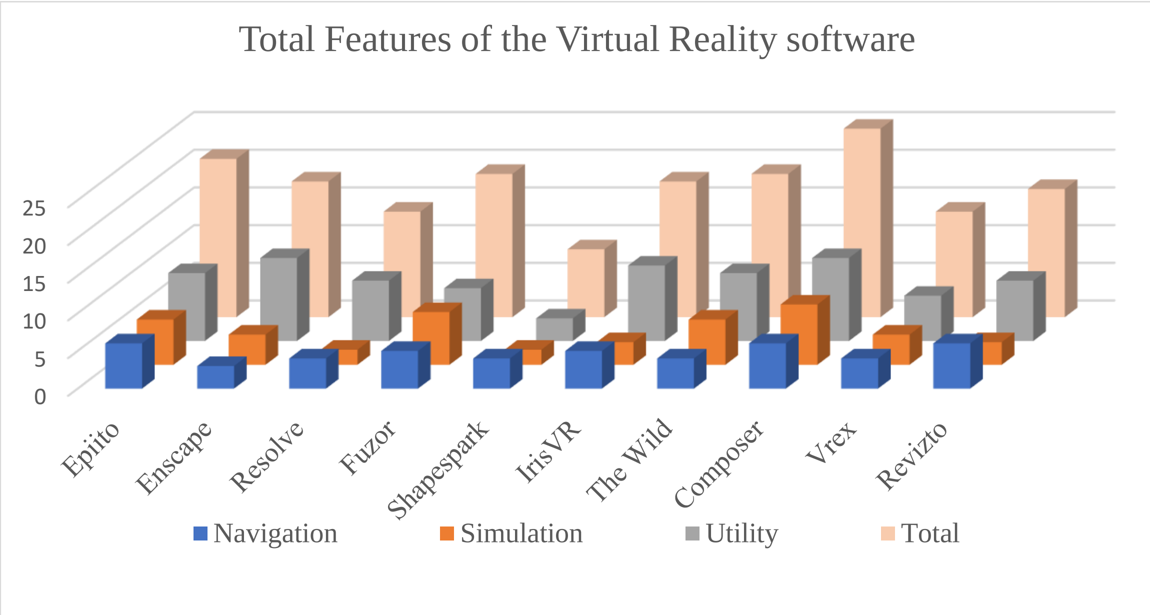
Table 9 - Simulation features

Moving objects in the scene can give the user the ability to test different parts of the building and adjust objects in the desired way and change the surface material for a better design. The interaction with objects enables the user to communicate with items that can be controlled, such as opening doors, windows, cabinets, and kitchen appliances. Still, many animations have to be created before the simulation is run, and only Wild and Composer can define those animations.

Light simulation helps the VR user alter the time of the day or the sun's direction to observe the impact of the shift of daylight on the building in the VR scene. Lightning simulation allows the user to monitor and adjust the lightning effects where new lightning sources have been applied to the building model. It is also useful, mostly when the day is set at night and artificial illumination becomes the primary lighting source. Object simulation allows the user to experience and learn from complex effects such as flames simulation, smoke, or sound simulation. These features are provided only by Fuzor and Composer. Epiito, also has the sound simulation, but rather than that, the other apps can only simulate the lightning.

Discussion

This study's ten analyzed software provides a wide range of options for architectural and construction companies at various levels of interest. They can apply virtual reality in their projects, from as early as possible, to obtain VR expertise, all the way to detailed incorporation in their design and project rendering.



The total number of features each software is providing in regards to navigation, simulation, and utility is shown in the graph below, where Composer, Fuzor, and Epiito seem to have the broadest range of characteristics. However, each program's user interface is different, and this can also have an impact on the person using the program. The three programs' user interface will be discussed below, but since Fuzor does not offer a free trial, meaning we did not test it, the user interface of Enscape will be described instead, which is the next program in line.

SimLab Composer

Figure 9 represents the user interface of Composer where you can create renderings, simulations, animations, and also automation for Virtual Reality. From the first days of installing the program, it seems to have a friendly user interface. It is not too crowded with buttons and features, but mostly the essential tools you need to create an interactive Virtual Reality experience for the design team, client, or end-users. [181]

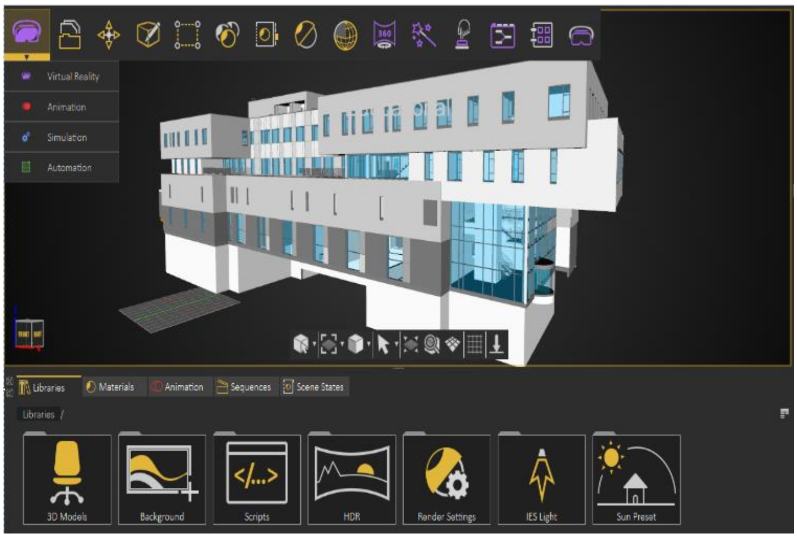


Figure 9 - SimLab Composer User interface

Epiito

Epiito (*Figure 10*) is offering the cloud and the studio version of the program, which have a similar user interface. The program allows users to communicate efficiently and visualize the virtual reality model. Still, in Epiito, the simulation feature is missing, but the mobile-based application is handy for new users to see what is happening in the model or what the stakeholders are planning. [182]

Figure 10 - Epiito Cloud Editor user interface

Enscape

Enscape (*Figure 11-12*) is a VR program that works as an extension to the BIM modeling software (e.g., Revit, ArchiCAD). In comparison to the development, such as SimLab Composer or Epiito, it is not a standalone tool. The user interface is quite a basic one enabling the user to move freely in the model and do certain things. Enscape is using a simple user interface from basic game controls. [183]

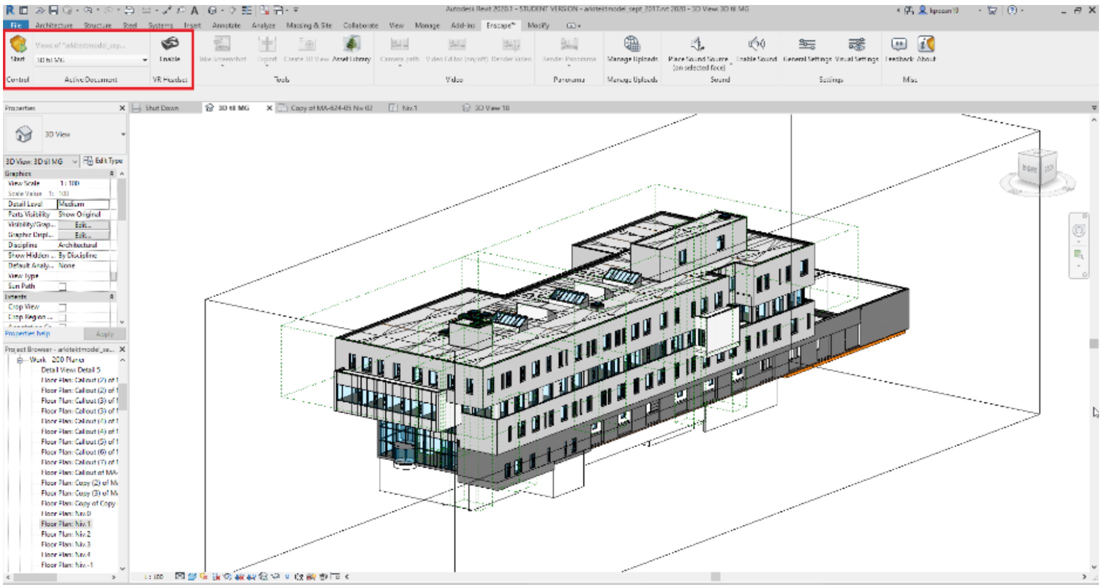


Figure 11 Enscape integrated as Add-in to Autodesk Revit

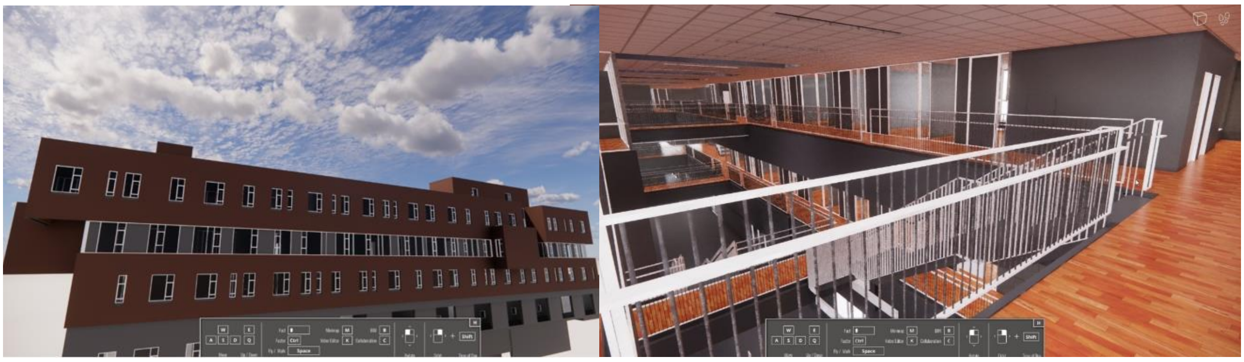


Figure 12 Enscape User Interface after starting the program from selected 3D views in Revit, outside the building (top view) and inside (bottom view)

Lastly, in addition to the VR capabilities tested in this report, Composer, Epiito, and Enscape also have many other BIM-based features that architectural and design companies may take advantage of. Composer itself is a 3D modeling software with rendering, animation, and file transfer capabilities. Enscape, on the other hand, is an add-on for 3D modeling software and allows synchronization between the models as well. Epiito has many communication and cooperation capabilities that will enable users to communicate with different stakeholders from the project live.

These virtual reality applications have different features and are mostly used to visualize the 3D model; therefore, individuals are resilient to buy such a program only for showing the model to the client and experience an immersive view to some extent. That being said, using the information gathered from this software and the literature review, an adapted contextual design of a new VR prototype is presented in the next chapter, Design of the Prototype.

More information about these software can be found in *Appendix A.*

Chapter 5. Design of the prototype

The chapter "*Design of the prototype"* presents an adapted methodology from the contextual design. It is the next step after gathering data from the literature review and the investigation of popular, widely used, and practical virtual reality tools in the AEC industry. The chapter's objective is to demonstrate a straightforward process and procedures for developing VR concepts and simulation, starting with data collection from professionals (architects, designers), modeling the processes, and interpreting the key issues, together with takeaway points from the literature review.

Based on the analyses' output, the visioning of the new ideas and directions takes place next. Components of the new system are captured in storyboards, and finally, the floor plan of the development with descriptions is shown in [5.5. User Environment design], followed by [5.6. Paper prototyping] for testing paper mock-ups of the system and concepts with users.

The final aim is to prepare foundations for creating a VR-based simulation that could improve communication and collaboration between the designers and end-users/clients, allowing future occupants of a public building to act as active participants in the design stage. The initial brainstorming process about different contextual design steps can be found in the *Appendix B.*

5.1. Contextual inquiry

In the following subchapter, the interpretation of the contextual inquiry is presented. Usually, the contextual inquiry contains data gathered by a team that observes the user's work and actions, what tasks they perform, and how they perform specific activities over a long period. However, due to this report's timeframe, the data collection was constrained to a set of semi-structured interviews conducted with people who work with clients and end-users in a building's design stage. Additionally, Contextual Inquiry consists of relevant input from the literature review to draw the bigger picture of the industry, find out how these processes are being held internationally, and map similarities with differences.

Table 10 presents the individuals who took part in this report by providing their knowledge and experience as data and their current job positions. The interviews were held either as online meetings or in-person using the tools available. The interview guide developed earlier uses the framework of Kallio et al. [20] for creating a qualitative semi-structured interview guide.

Interviewee #1	Beloslava Ivanova	Architectural Technologist
Interviewee #2	Lucija Thomsen	Project Leader, Architect Assistant
Interviewee #3	Daniel Zah	Architectural Technologist
Interviewee #4	Barbara Adamska	BIM Manager, Architectural Technologist
Interviewee #5	Peter Hyttel	BIM Manager, ICT Coordinator
Interviewee #6	Martin Hauge	BIM Manager

Table 10 - Persons interviewed for this report

After the interviews have been conducted, the information is reviewed, and the transcripts were fixed from mistakes. The full transcripts are found in *Appendix D.*

After an overview of the data, taking notes, and brainstorming, the next step was to extract the sections from the text relevant for our report and to conduct the process called coding qualitative data, which means brainstorming and coming up with shorthand labels or codes that describe the content of the section. The process is repeated for all the interview transcripts, highlighting potentially interesting phrases that fit existing codes already assigned or inserting new codes until the end of the transcripts. This coding representation can be found in *Appendix E*. These codes will allow us to gain a condensed overview of the main points and common meanings that recur throughout the data.

The next step is to identify recurring themes among these codes. These topics are generally broader than codes. Therefore, several codes are combined into a single theme, or some codes can become themes as well. (*see Figure 13*)

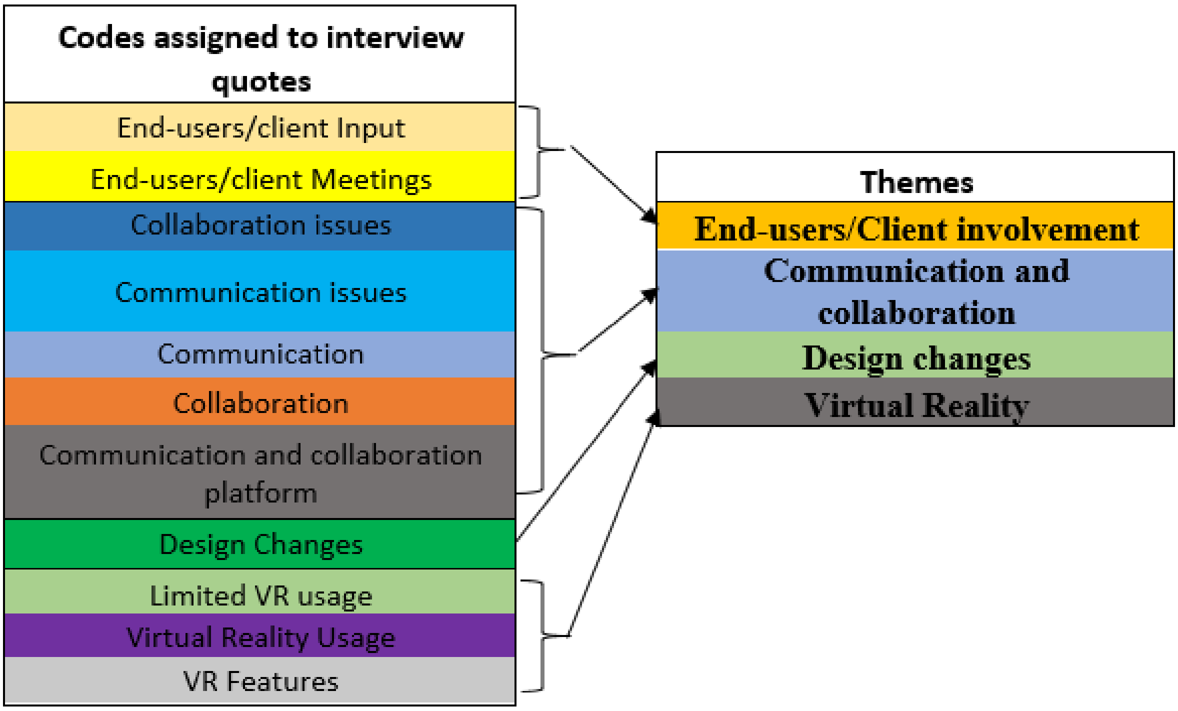


Figure 13 - Assigned codes + themes to the interviews

The vital procedure was to make sure the chosen codes and themes accurately represent the data to extract the true meaning. After codes were assigned to the interview quotes and categorized with related themes, it resulted in four main topics of the relevant key contributions.

End-users/Client Involvement in this report refers to how the client and end-users are included in a public building design stage. The collected data from the interviews overall shows their involvement in the project to some extent. For example, the Project Leader explained how their meeting with clients occur - by showing renderings, videos, or printed materials as documentation (Interviewee #2). The BIM manager (Interviewee #4) also said, "*It is a common misconception that a client/end-user without construction experience is not valuable to the design team. In practice, gathering their views, expectations, and potential limitations (e.g., regarding disability) significantly shortens the initial planning phase and allows the designers to focus on the most optimal solutions.*" The end-users are involved to some extent, but most of the interviewees kept saying client, not necessarily end-users. In the case of a public project, the client might not have enough information about the future building's interior or how the future occupants will conduct their duties, or how their environment should look.

Communication and Collaboration in this report refer to issues, platforms, communication methods, and collaboration between the stakeholders in the design stage of a public building. Overall, the data shows that every interviewee encounters communication or collaboration issues. Several Building Constructors and a Project leader stated they encounter collaboration and communication problems within different tasks they have to handle. (Interviewee 1, 2, 5) Some BIM managers use Dalux, Dropbox, email, phone calls, or their database to collaborate and communicate with each other. (Interviewee 2 & 6.) Even though they all seem to know they can use different, more effective tools for collaboration and communication, after all, it might be the economy that is restraining the adoption of new tools.

Design Changes in this report refers to mistakes, errors, or misunderstandings from the design stage, resulting in costly changes later in the development of the public building. All five interviewees are presenting different scenarios of design changes from the projects they've been working on, such as: "*Change from the concrete walls to the glass curtain walls.", "It seems design changes, later during construction, are still upcoming and leading to many challenges." "We encountered a significant design change in the construction phase. As a result of miscommunication and missing information.",* even interviewee #5 who has 20+ years of experience in the field, stated that "*Yes, all the time we encounter design changes,"* these confirm the communication and collaboration issues noted above, which in the end lead to design changes in the construction phase.

Virtual Reality in this report refers to what extent virtual reality is used within the company overall, as well as what input these individuals can give us to help with the development of the VR simulation. Virtual Reality seems to be still something for the future for some companies as they say: "*I tried VR headset for a driving experience which seemed realistic or once game application shown by a friend.",* but most of them are using VR applications to some extent, for walkthroughs, general visualization or even clash detection. (Interviewee 4 &5) On the other hand, they were giving some input for a VR simulation in the design stage, which helped us in the development of the app:

- Design solutions, changing materials, furniture, add new objects while communicating with others,
- Real-time changes to the design, report, and comment issues,
- How to get from one point to another in the building,
- Record the path when they escape, see if it's the fastest route,
- Web-based application.
- Collaboration between the app and 3D modeling software (Revit, Rhino, ArchiCAD) (Interviewee 1,2,3,4,5 & 6)

The gathered data helped understand the possible users of the prototype and what kind of features they would expect in the simulation, their problems in the design stage, and how virtual reality is used in the industry in Denmark.

5.2. Interpretation and work modeling

The following subchapter contains the interpretation of the data gathered through the literature review and the semi-structured interviews. As a result, the design phase's work model is constructed to comprehend the issues and develop a shared understanding of how communication and collaboration processes are managed between the end-users/client and the design team.

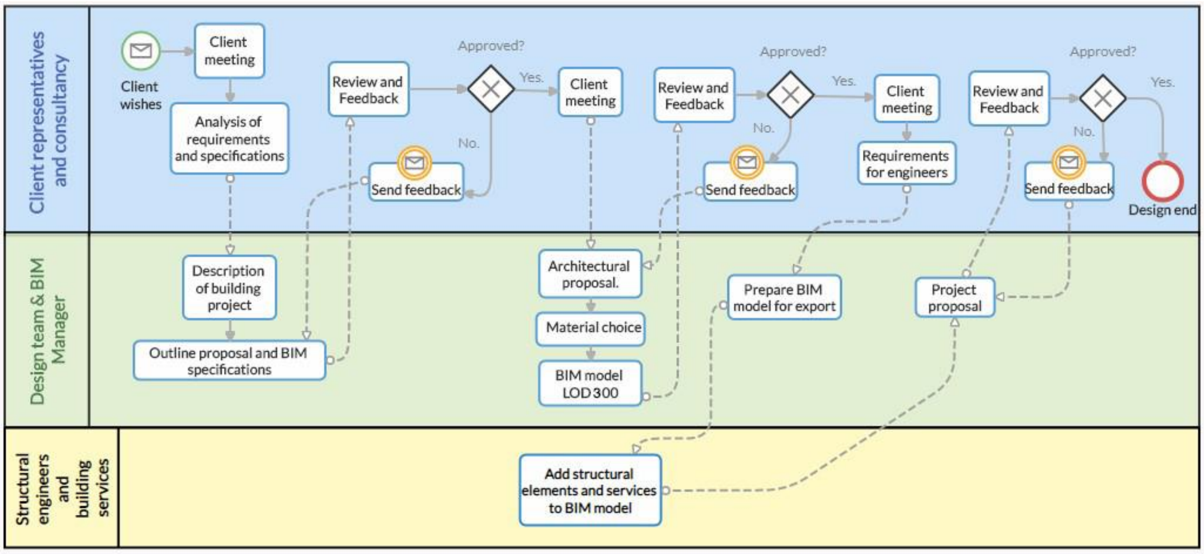


Figure 14 - General representation of the Work Modelling in the Design Stage

The figure above displays work modeling based on the flow model's principles and the sequence model for a general interpretation of the current AEC industry state. The flow model refers to communication activities between participants in the organization and teams necessary for coordinating different tasks. On the other hand, the sequence model presents steps taken to complete every goal. The graphical nodes from BPMN were used to create *Figure 14*.

The Interviewees highlighted the importance of including standardizations and building regulations (BR18) in the designing process from the early design stages while implementing requirements and wishes established from the client meetings. **Interviewee #1** explained that her duties in the company she works in include designing activities according to the building regulations and guidelines they use, helping colleagues with drawings, participating in the meetings with the clients and people they work with (engineers, third party investors, etc.). For a typical complex project, the dialog between their architectural firm and investors begins from the beginning to form main guidelines, agreements on what materials to use, and what usages to consider. Sometimes it happens that there is an exterior designer appointed by the investors to work with.

Moreover, **Interviewee #4** provided a point of view on involving clients and end-users. *"My responsibility is not primarily to just meet the ISO 19650 standards and local regulations but to enhance the experience on the client and end-users' side. We provide 4D simulations, VR, and real-time rendering to involve the project owner and make them aware of potential changes, risks, and solutions across all the design and construction phases. Each project goes* *through a standard "BIM routine" (clash detection, quantity-take-offs, 5D), and the design is reviewed at regular intervals."*

On the other hand, **Interviewee #5** expressed the complexity of big public projects. He said it is a complicated process because usually, there is a long and extended design phase where common understanding needs to be formed between participants of a project. The stakeholders may have varying ways of working. Therefore, when different cultures meet, the design phase is critical to overcoming these issues. The designers aim to explain to building owners during workshops exactly about the processes to provide a broader view of what is going on, to avoid miscommunication. Additionally, interviewee #5 said that they work with the end-users to understand their needs and specific requirements (for example, in hospital and office projects).

During **Interview #1**, it was highlighted that end-users as the future occupants of a building do not usually come into the designing process until the project design is finalized. It can lead to frequent modifications later in the development, even in the construction phase. On top of that, this interviewee said that clients and end-users are sometimes confused about what they want and do not specify their needs. The communication is also more difficult for them when it is through the investors to reach the intended users.

Both **Interviewee #1** and **#2** stated that information is displayed to the clients, their representatives, and end-users in the form of presentations with project books of all the main concepts, renderings of the building, videos, sun analysis simulation, and any relevant printed materials. They stated that clients do not have the usual professional knowledge to understand drawings (floor plans) entirely. Therefore, renderings are a more satisfying option for the presentation.

From the literature review, it was discovered that it is not a common practice to involve the end-users before the building is ready unless the clients are also the end-users. [35] Moreover, the researchers [57] [50] [56] refer to a lack of functional measures of BIM models for working with the clients/end-users more actively. That formal presentation forms (pre-prepared information, drawings, videos, models displayed on screen or paper) are the static types of interaction that does not get essential intel from the clients. It was also noted that sometimes physical, cardboard mock-ups of the models' parts are made for the complex building to involve the end-users in the process. However, it is a consuming procedure to construct even one scenery and may not seem realistic enough.

At the same time, **Interviewee #3** also pointed out the primary demonstration preference to the end-users as physical models because then the end-users can investigate themselves the mock-up of a building to express their needs. However, he added that they rarely work with the end-users.

On the other hand, **Interviewee #4** added a more technological approach for the presentation **- "***We provide 4D simulations, VR and real-time rendering to involve the project owner."* and explained further, *"We use VR for design competitions only. For regular clients, we organize formal meetings with design reviews and walk-through in BIM 360 and video representations of simulations."* During **Interview #5,** it was expressed that the company uses many forms of demonstration methods during the meetings with clients/end-users: "*By all means possible we present the project to a client, by PowerPoint, VR, Excel, writing, showing mock-ups and physical models, digital models*."

Interviewee #6 said that traditionally they have been communicating design via paper drawings, but it tended to be a complicated process to express intentions because end-users (for example, a nurse or a doctor for a hospital building) do not have the same understanding as the designers to read the technical plans. The interviewee added that now on top of drawings, they try to include the end-users with VR live walkthroughs in the model. They use this method with end-users to make sense of the geometry, design proposals and ease explanatory processes. Furthermore, the end-users could be better understood and how they are looking at objects in the model: "*the basis of their understanding is totally aligned with what they do. That gives us a huge advantage in communicating our design and also maybe in some of our difficulties in our design. This is a great communication tool for us to watch the non-knowledgeable person.*"

Interviewee #6 also explained that for big projects, the designers in his company use a specification database to gather information about all rooms with sizes, what utilities and furniture should be added, and requirements. When they meet with clients, the database is updated. Based on that information, 3D models are created.

It can be summarized that the architectural companies use varying methods to communicate the design concepts to their customers and end-users and to investigate their actual needs and wishes. It depends on their resources, what they are used to do, and the project's sizes. They also have different experiences about the end-users that are not necessarily the clients. The companies either include them to some extent, depending on the project or almost not at all.

From the researchers' standpoint, it is indicated that each project needs special considerations as there are different types of end-users occupying the spaces – hospitals, universities, office buildings. [36]

Furthermore, user involvement enhances increased assessment of functionality, usability, consistency of requirements, and product development efficiency. [19] On top of that, it could add more effective and efficient results if the end-users were to participate in the design process. [50] It was also highlighted by Nikolic et al. [40] that the design review applications should consist of functionality, accessibility, safety, and effectiveness of the spaces in the buildings for future occupants. Such a solution could be implemented as a VR design review tool.

The interviewees encountered numerous design changes in the construction phases during their professional experience. There could be various reasons for the issues that could be eliminated to some extent if different actions were to be arranged during the design stages. The interviewees stated that the design changes usually come from communication issues, misunderstandings, or information lost.

Interviewee #5 explained that the changes might originate from builders' demands or errors on the site. In contrast, **Interviewee #4** highlighted the end-users' position - by saying that understanding their 'views, expectations, and potential limitations can significantly shorten the initial planning phase. At the same time, it can allow the designers to focus on the most optimal solutions. Moreover, the repeating pattern appeared based on what professional designers have experienced. The changes have resulted from either collaboration, communication issues between stakeholders, and miscommunication with the clients/end-users.

Building owners and intended users usually cannot express their thoughts or are not entirely sure what they wish for during the designing process. The cause of it could also be found in the static form of presentations that do not include an interactive feature for allowing the end-users to show what they mean, or they cannot understand what the designers demonstrate.

There can be found a compelling contribution from the literature review concerning design changes. The modifications in the construction project still happen even with the growth of the technology use. Every change in design increases costs and time. [17]. According to the study [30], involving the end-users in the designing stage can decrease unexpected expenses resulting from changes later in the process.

Moreover, it is frequent the end-users are not satisfied with the construction and designing choices of a public building because of difficulties from daily tasks, the study by Ayuba and Adedayo says. [39]. Another compelling takeaway point from the literature review is that improved communication and collaboration between stakeholders might be accomplished using VR tools for the design review. [92], [136]

Virtual Reality technology was investigated in the previous chapters of the report, along with other extended reality means (Augmented, Mixed Realities). The sources from the literature review pointed out the potential the technology brings to the AEC industry. For example, VR technology can be implemented already in the early conceptual design phases to solve various issues connected to a high degree of abstraction, planning, and ideas built in the development [60], which can help designers to get the requirements/wishes from the future occupants of the building.

Moreover, VR technology is considered by the researchers as solutions that offer more dynamic techniques with a focus on user experience and interactive communication [59]. VR and the use of serious gaming can provide immersive depth to the BIM models and storytelling experience with both first and third-person perspectives. [75], [76], [47]. It means prepared simulations in a game engine can be converted into different mode viewing and device type – for instance, VR headset and controllers, Desktop-View with movement via keyboard and mouse, and even mobile devices, phones tablets. VR is also recognized to give its users the ability to feel as if they were next to the displayed objects. They can investigate presented information in such a virtual environment. [54] Therefore, the designing team is able to display and parts of the houses or the whole modeled structures in various VR simulations that represent the future building.

VR is implemented as an interactive mechanism to BIM models to simulate the virtual world in 3D and 4D time and as a decision-making tool in the design process. [132] VR integrated with Serious Gaming scenarios, and VR can significantly improve the knowledge and self-efficacy of the end-users during evacuation training to prepare future occupants to act effectively against dangerous situations such as fire emergencies or earthquakes. [78] VR is also found to improve the design of signage. [139]

These applications provide concepts that the designing team can use during the early phases of project development. They can use the immersive simulation for emergency scenario testing or preparing efficient signage to receive commentary of the end-users who are to occupy the building but are not yet familiar with the spaces. It advocates possibilities to adjust the design during the early phases to minimalize the risks of unpractical solutions.

There were distinguished similar statements from both conducted research on VR and AR-based on various publications and output from the interviews about collaborative advantages of these immersive technologies. For instance, **Interviewee #2** explained the use of AR platform with BIM viewing options as a walkthrough, "*Comparing the hospital project where we use Dalux to the other projects, it definitely helps with the communication issues*," and "*I have just experience with Dalux* (when asked about VR/AR experience) *where you can go through BIM model, collaborate, see virtual objects on the site*." **Interviewee #4** and **#6** said that they use Ensacpe for VR integrated into the BIM platform, Autodesk Revit. It was mention by Interviewee #4 and #5 that they have worked with end-users/clients by the use of VR. **Interviewee #4** said that it was enjoyable for their clients to experience the building and make some changes before proceeding with the design. VR has also helped them with design reviews, including clash detection and giving the client a real opportunity to express their input. On the other hand**, Interviewee #6** stated that Escape does not support collaborative meetings as of today (2020) and is more like viewing VR software, where a user cannot really interact with the design.

Interviewee #5 pointed out that VR is used in some projects depending on the client's position in the undertaking and available facilities where it might not be needed. However, he thinks that the immersive technology is suitable in the early phase when it has the most potent effect to influence results in the later stages of the design development. Furthermore, Interviewee #5 highlighted the use of VR for visual inspections when they have a detailed model. The participants then can move around and investigated a building of realistic appearance in the virtual environment.

The interviewees provided essential points to consider about VR and how best to use it. Clash detection is frequently mentioned, which can be regarded as a useful VR attribute, even if the model is just investigated visually by the designing teams and the end-users.

VR is used to some degree in the construction industry, but many companies seem not to be familiar with the potential of the VR tools, and many times the economy is the argument against implementation. As Gonzalo et al. mentioned in his paper [54], BIM models and VR experience can support the understanding of building projects in the early stages of design development. The interviews' information is admitting that it is a useful idea; however, they might lack personnel to handle such things.

The last question of the interviews referred to VR features and the software implementation, what the interviewees' opinion is about the VR simulation's component. **Interviewee #1** said VR could help get feedback on what the users think and genuinely want. Moreover, **Interviewee #2** stated she would like to be able to investigate connections in the building with different design solutions and features of changing materials, furniture, textures, adding new objects, and communication with others while the modifications are being implemented. **Interviewee #3,** also referred to similar designing capabilities for VR.

Interviewee #4 demonstrated the need for features for real-time changes to the design, design review options, report and comment, and issue allocation**. Interviewee #5** added to the topic that VR simulation could have a timer option to see how much time it does take for users to get from a specific point to another. It could be combined with visible footprint information shown in the model about distances for documentation to deliver to a client. **Interviewee #6** expressed that a good idea would be to develop an optimized connection between VR software and designing programs to synchronize back the immersive environment's changes. He also added that VR simulation development should be turning onto Web-based apps instead of a standalone program.

The information from all the Interviewees provided crucial feedback about VR features, which to consider. When combined with investigated previously existing VR solutions, the decisions about the prototype's content could be made. Interpretation and work modeling the image of how the architectural companies typically work in the industry helped formulate the ideas for the next step of the Design of Prototype – Visioning. Professionals' expertise learned from the interviews also supplied constructing the foundation for the simulation prototype.

5.3. Visioning

The Contextual Design's visioning step displays directions and new ideas that could improve the overall workflow in the designing phases when the end-users and clients are involved in the proposed immersive and interactable environment. The users can experience as if they were inside the soon to be built buildings. They can interact and express their thought-process behind the most suitable solutions for their future workplace.

The important part is to find the most opportune moment to integrate the end-users in the design stage. This process is shown in *Figure 15*, which demonstrates a construction project framework in the design stage and where the end-users can be integrated.

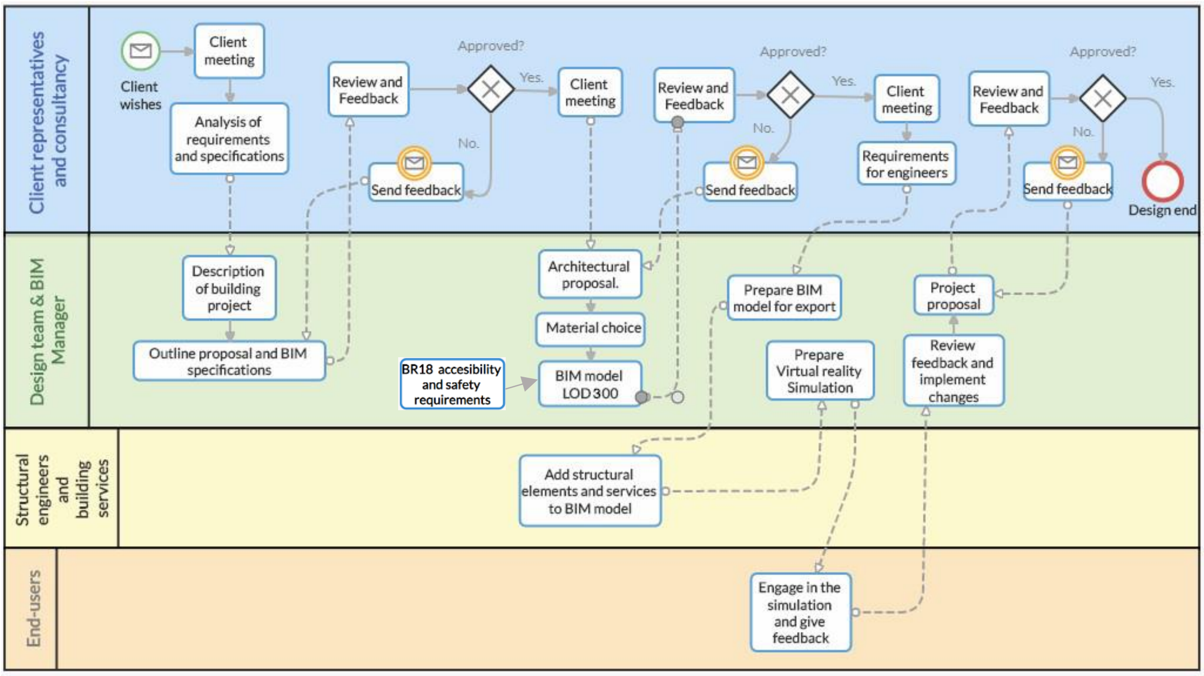


Figure 15 - The proposed framework for involving end-users in the design stage

The simulation concept is visioned in *Figure 16*. It focuses on being developed in a game engine (in this case, Unity3D is used as an example) after the BIM geometrical model with architectural solutions, textures, and possible furniture choices are concluded. When a simulation prototype is created, the users are invited to participate in the process. Their role is explained. Additionally, each step is planned to have an introduction in the simulation. The framework is expected to include a Questions & Answers session for the participants to understand their involvement in the process altogether. In the end, the game is finished with a report that consists of feedback along with possible changes to be discussed in regards to the design.

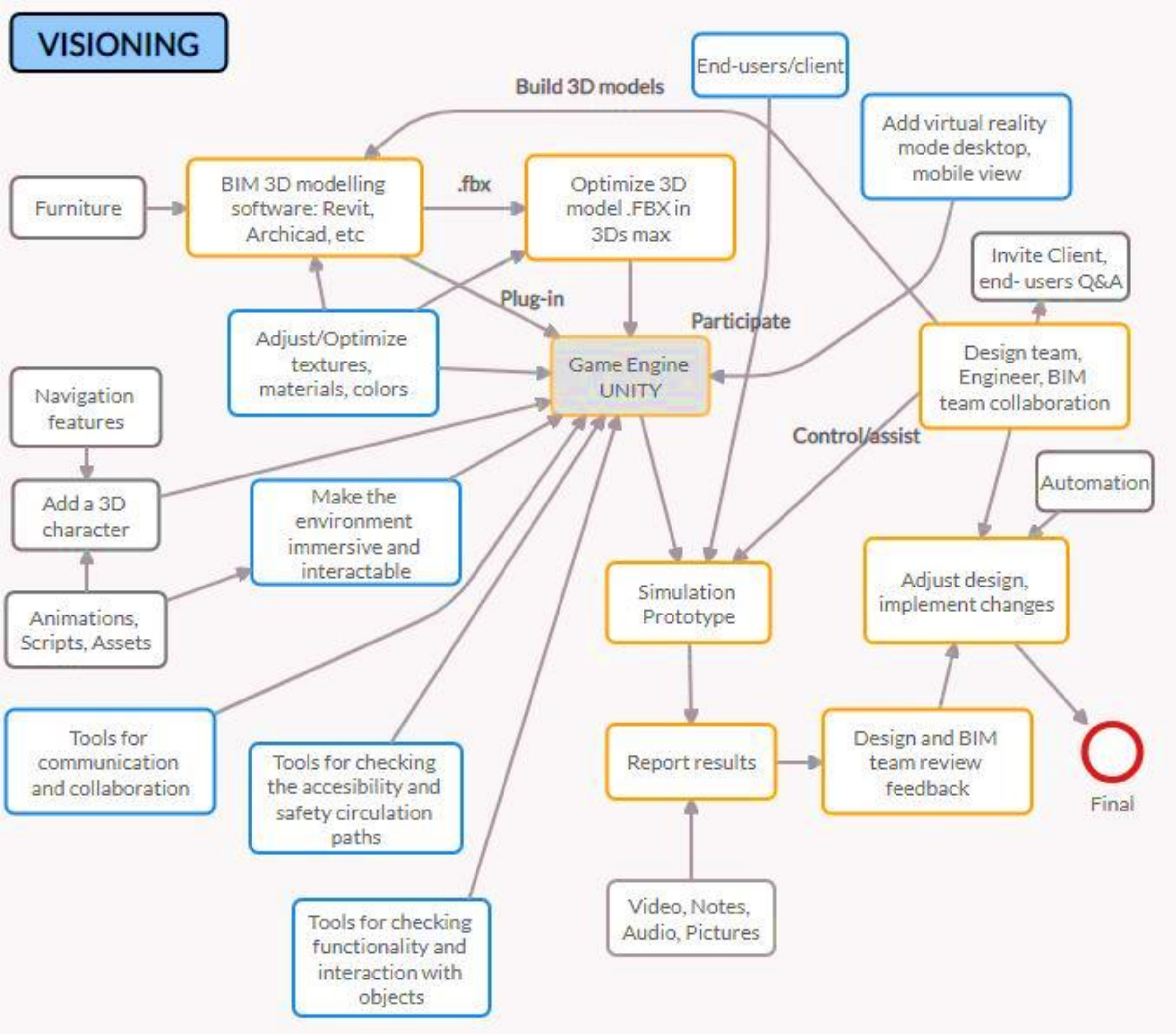


Figure 16 - Visioning

5.4. Storyboarding

The Storyboarding step (*Figure 17*) in the development process is incorporated to present various functions and narratives of the major components inside the immersive simulation with incorporated activities that happen before and after the game is created.

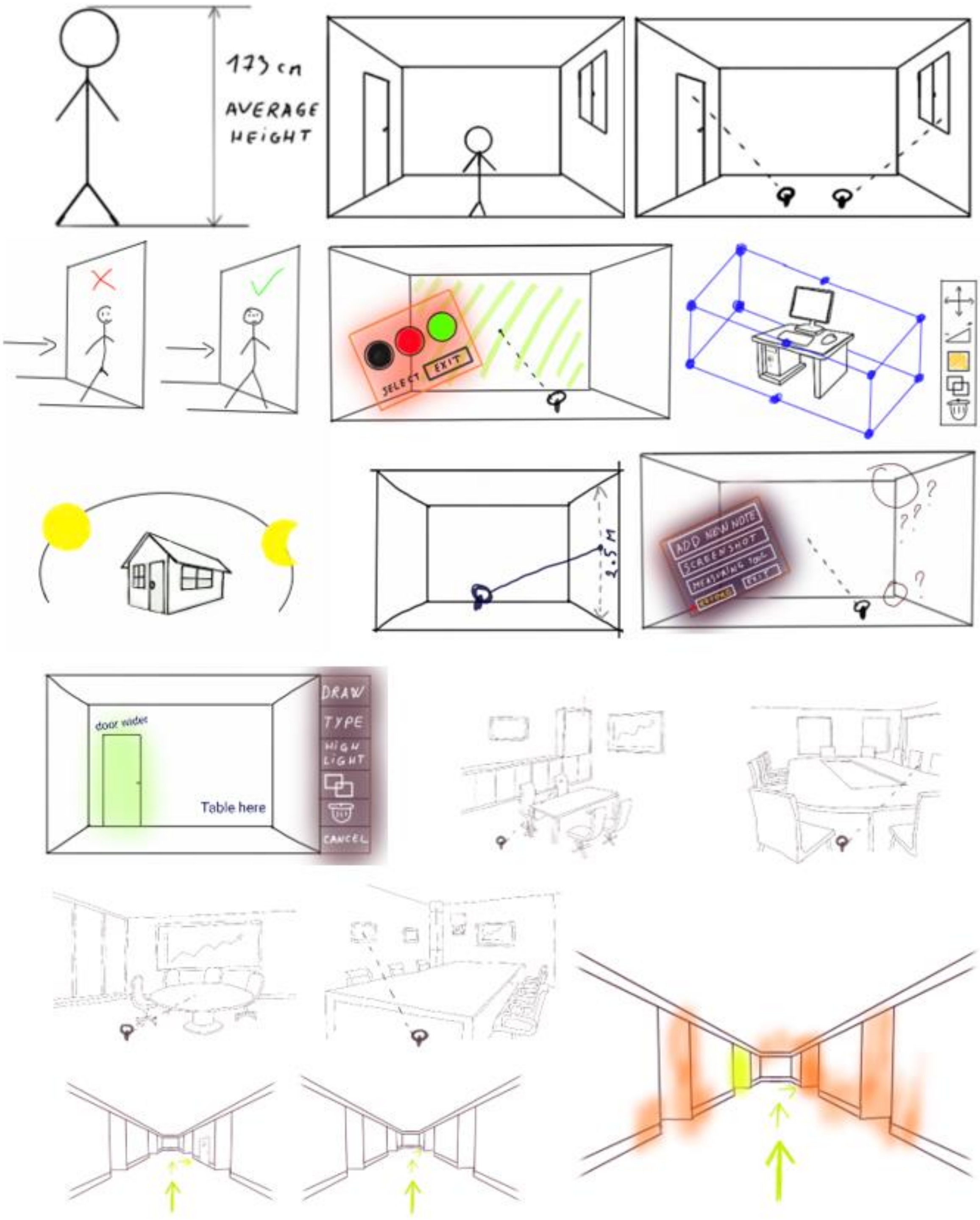


Figure 17 - Storyboarding of the prototype

The next two *Figures, 18 & 19* present a sequence model of both the Designing Team and BIM Team and provide a background for creating the storyboards. After producing a 3D model with LOD 300 in the modeling software (Revit), designers are preparing an export file for the development of the simulation. Furthermore, they assist BIM specialists in creating the program prototype for involving the end-users and the clients. [Step D5].

The storyboarding is displayed in steps B4, B5, and B6 to demonstrate the game's dynamic characteristics – "Add 3D Character and Navigation Panel", "Add Game Logic," and "Create Game Features," respectively. Moreover, the scenarios are incorporated in the Storyboards from B7.1 to B7.4 that provide specific tasks to be completed by the simulation users.

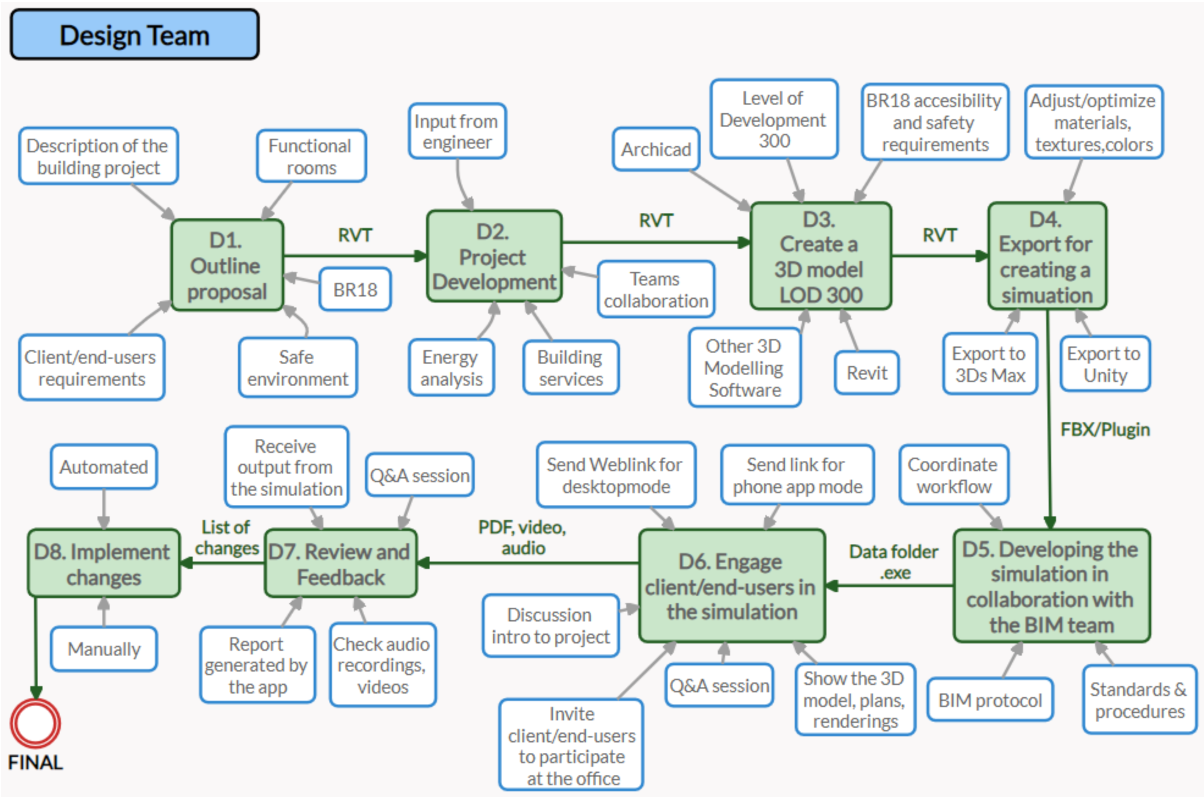


Figure 18 - The sequence model for Design Team's work

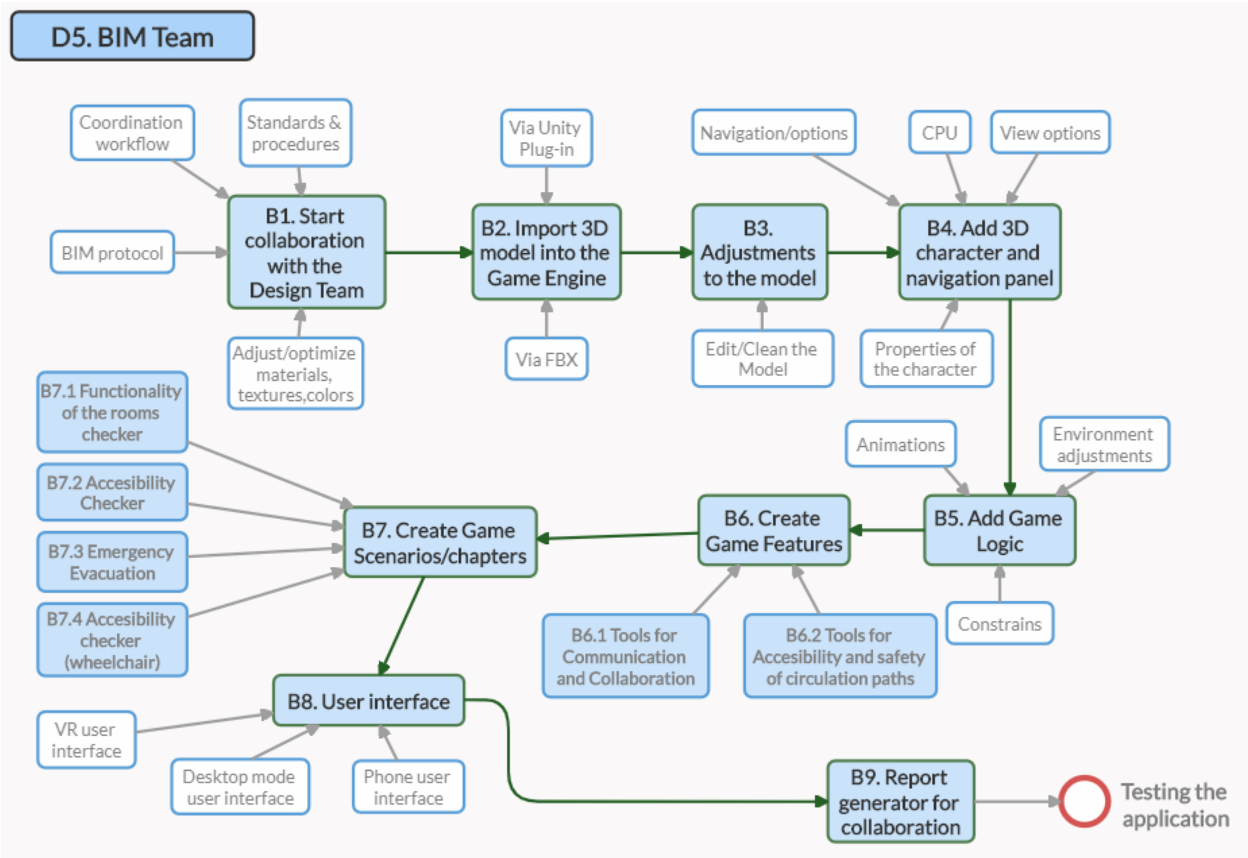
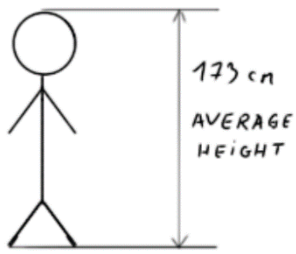


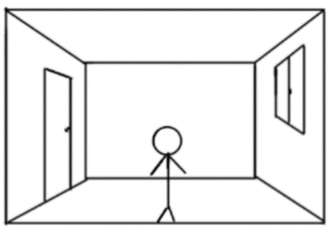
Figure 19 - The sequence model for BIM Team's work

[B4] Add a 3D character

- The 3D character will provide a starting point for the client/end-users, who will play the simulation.

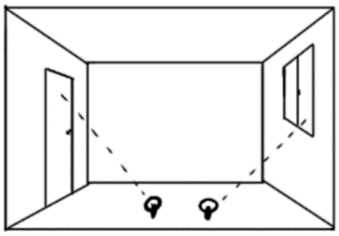


- View options:
  - VR head-mounted display will create an immersive view as close as possible to reality
  - Desktop view:
    - **First-person** will allow the user to see the same view as the VR headset.
    - **3D view** will allow the user to see himself using a wheelchair, for example.
  - The phone view allows users to view the model from anywhere.



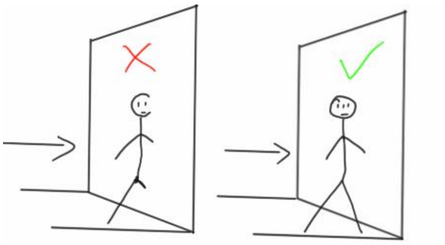
- Features:
  - Walk Physically (Oculus Quest)
  - Walk with a joystick at a normal speed of 5-6km/h

- Teleport to a certain location with a joystick or predefined location.
- Fly mode allows user to get a better perspective of the building
- 360 degrees rotation view.



[B5] Add Game logic

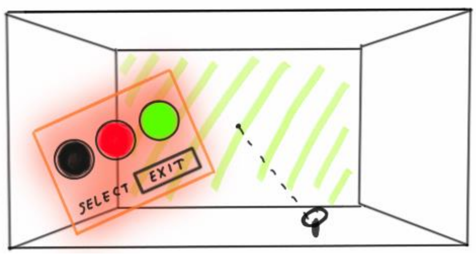
- Animations. The 3D character must interact with certain objects to test the accessibility and functionality of the building or a specific area.
- Animations needed:
  - 3D character (Joystick, WASD keys, Arrows)
  - Doors/windows (Open by grab or click)
  - Furniture moves around (Tables, shelves, chairs, etc.)
  - Wheelchair animation (for accessibility scenario and evacuation)



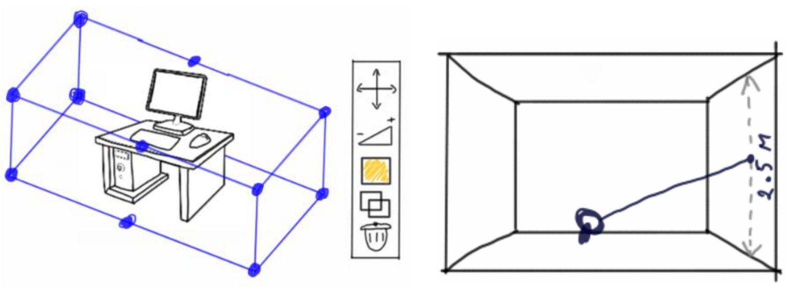
- Collision detection prevents the character or objects from going through hard surfaces such as walls, doors, and floors.
- Daytime adjustments animation. Sun adjustments to the shading effect in the rooms and daylight effect and an artificial lighting effect.

[B6] Add Game features

- B 6.1 Tools for interaction with objects
  - **Material/color/texture change**. The user will be able to select from the popup menu the aspect of walls, floors, ceilings, and furniture as desired.



  - **Object edit.** Users will be able to furnish their working environment as desired or propose different ideas of office design for example.
    - Move
    - Resize
    - Change color, texture
    - Duplicate



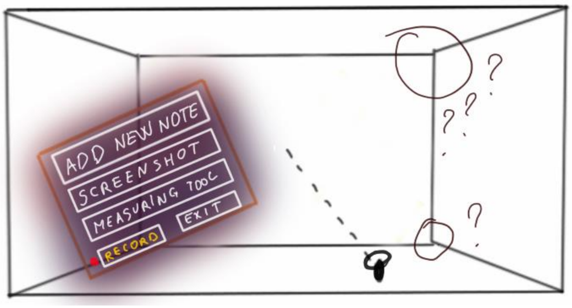
- Delete

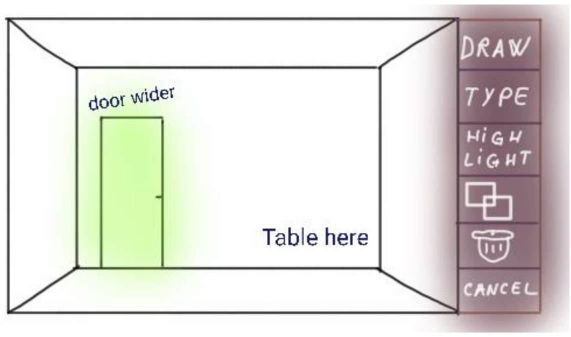
- **Measurement tool** for checking if spaces seem to be odd

- B 6.2 Tools for communication

To generate a report with the user's input, there is a need for different tools to create information such as:

- Add notes pinned to specific locations
- Screenshot, highlight, draw or write on
- Record a message
- Leave a measurement if the space seems odd
- Multiplayer communication





These tools will help the users to effectively communicate their experience in the VR simulation to the Design team.

[B7.1] Functionality of the rooms checker (Scenario)

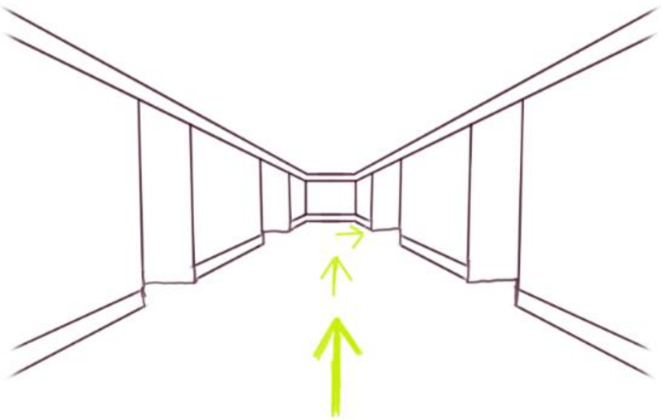
In this scenario, the user must complete all tasks to help the designers create the most proper environment for their daily work and duties.

- Task 1. Find the room [room name] and design the interior with furniture and textures/colors from the menu.
- Task 2. Compare your design with three different options generated by the game and rate the designs from the most functional design to the most unfunctional.
- Task 3. Collaborate with another teammate to design together with a meeting room, common room, office, etc.
- Task 4. Go through a full day, adjusting the lighting and shadowing of the room. Rate the room functionality from 1 to 5.

[B7.2] Accessibility of the rooms checker (Scenario)

In this scenario, the user must complete all tasks to help the designers create an easily accessible environment for their daily work and duties.

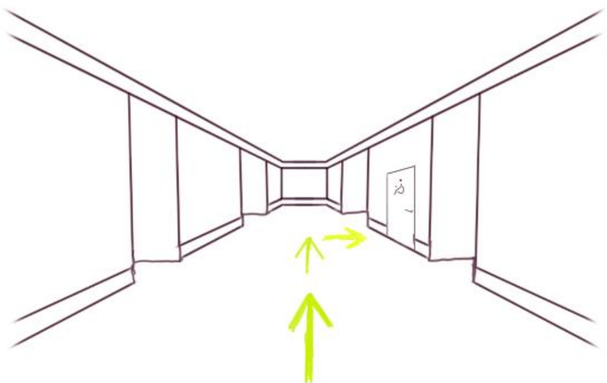
- Task 1. Walk freely through the building for 5 min. Rate the walking paths from 1 to 5. Screenshot and annotate what seems odd.
- Task 2. Follow the walkthrough path by walking or by joystick. Is access practical? Rate your experience from 1 to 5.
- Task 3. Open any five doors and five windows and rate the following questions: Placement of the window/door? The direction of opening? Size of the window/door? In the case of negative feedback, please take a screenshot of the specific door/window.
- Task 4. Are the common areas close by almost all rooms in the building? (ex: Toilets, Printing rooms, Laboratory, Kitchen)? Suggest a new location.



[B7.3] Accessibility checker for persons in a wheelchair (Scenario)

In this scenario, the user must complete all tasks to help the designers create an easily accessible environment for their daily work and duties.

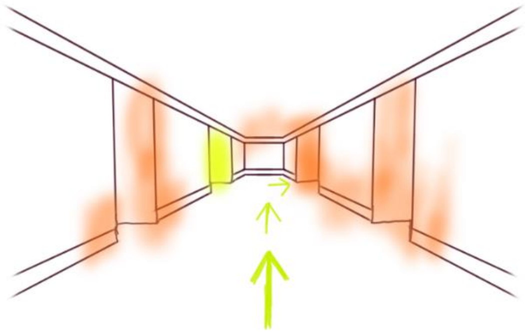
- Task 1. Get on the wheelchair and freely go through the building for 2 min. Rate the paths from 1 to 5. Screenshot and annotate what seems odd.
- Task 2. Check if the toilets are handicap friendly.
- Task 3. Follow the path to the different locations and rate the experience from 1 to 5. Screenshot and annotate what seems odd.



[B7.4] Emergency evacuation path checker

In this scenario, the user must complete all tasks to create an easily accessible and safe environment for their daily work and duties.

- Task 1. Escape from a specific point teleported in the building with the help of arrows.
- Task 3. In case of a fire emergency, find the firefighting equipment located nearby.
- Task 4. In a fire simulation, some escape routes can be blocked. Escape from the building using alternative routes. Time will be recorded.



5.5. User Environment design

User Environment design from *Figure 20* summarizes the new floor plan for the developed system, using BPMN annotations. It consists of steps that need to be taken before, during, and after the simulation process is concluded. The below diagram presents the process of inviting users to participate until implementing the changes to the BIM models architects will prepare for the finalization of the design.

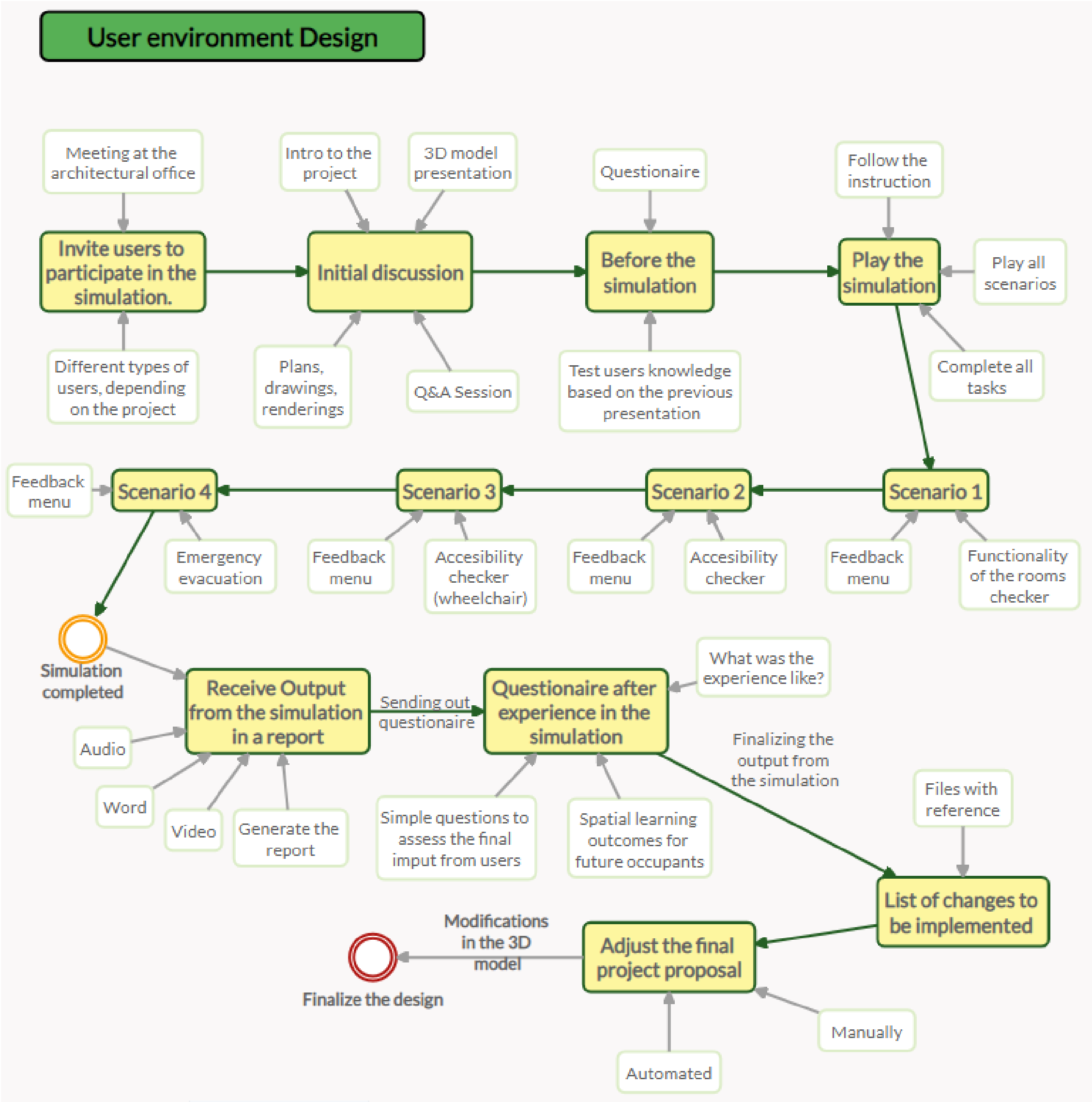


Figure 20 - User environment design

The new system framework was constructed based on the literature review, conducted interviews in the Contextual Inquiry chapter, and brainstorming sessions for Work Modelling, Visioning, and Storyboarding. The guide includes the User Environment Design of the VR game prototype and processes needed to be complete before and after the end-users/clients start "playing" the immersive simulation.

Framework – detailed step-by-step end-user involvement in the new system from both the Designing Team and BIM specialists involved in the process

1. **Outline proposal** – during the first designing phases, the conceptual process about building requirements, architectural aesthetics, and client meetings are conducted to gather essential data about project description, purpose, and the idea behind the undertaking and overall concepts that drive the specific design. Various proposals are demonstrated and explained to the customers and their representatives. Accessibility and functionality needs are specified according to building regulations, including a safe environment.

2. **Project Development** – the design is developed further, including inputs from different invested professionals such as structural, energy engineers, and building services while supporting the necessary analysis of acoustic, performance, and calculations. Architects, Engineers, BIM specialists, and other project participants collaborate, share their work and create virtual models following clients' wishes and project descriptions.

3. **3D model with LOD 300** – it is the product of the collaboration between BIM and designers who have already included necessary analysis from different specialists. The 3D model can be made in any 3D modeling software that enables either export as FBX file, plug-in converters, or direct transfer for use in-game engines.

4. **Exporting for creating a simulation**

After a model is prepared with all the design solutions the architects want to present to end-users/clients, the building representation is imported to the Unity game engine for the simulation development. As explained in [3.3.3. Export from Autodesk Revit to Unity Gaming Engine] in the literature review, there are few ways to export from BIM modeling software. The most common workflow involves Autodesk 3Ds Max as the middle step between a 3D modeling program (e.g., Autodesk Revit) and a game engine (e.g., Unity). The model is optimized and prepared with textures and materials that are complying there. Other methods include plug-in solutions that can export the model directly. The choice of solution depends on the designer's preferences and resources as some extensions are paid options or only have trial versions. For example, when someone uses Simlab Composer, they can optimize the file there instead of 3Ds Max.

5. **Developing the simulation in collaboration with the BIM specialists** – The architects/designers assist in producing the most suitable workflow in the game for receiving end-users' input. Agreed standards, procedures, and BIM protocols are followed. If necessary, the imported model's materials and textures are adjusted according to the architect's recommendations. Fundamental features and scenarios are developed.

6. **The end-users / clients are invited to participate in the simulation** – it can be either conducted at the architectural office or online. Before the meeting, the participants' profiles need to be assessed to fit corresponding tasks prepared by the designers. The following questions should be answered before starting the simulation process: Who are they, and what is their role? Which part of the building will they occupy? Is every step of the simulation relevant for them? This is important because, in the complex structure, there are different types of users. Depending on the project, they can provide a unique perspective when their interests are aligned with the content of the assignments in the game. For instance, students in the university building should be appointed for design review tasks around study rooms or lecture halls and not technical spaces or offices where they do not spend their time daily.

7. **Initial discussion** – Introduction in the form of a short presentation and Question & Answer session takes place to integrate the end-users/clients with the purpose and what is going to happen during the simulation. Moreover, the 3D model in BIM viewer, plans, drawings, and renderings are presented. In the end, a simple questionnaire is given to test their knowledge based on the previous presentation.

8. **Scenarios are completed by the participants –** four scenarios with different assignments are presented to the end-users/clients. Throughout the process, the data about their needs,

wishes, and experience is collected by the designing team - actions taken in the simulation supply the development of the final design that fits all the requirements. The scenarios are based on functionality and accessibility factors of the building, and the individual spaces, including testing safety of the environment with the emergency simulation and measures to escape as fast as possible. Moreover, it consists of an application for efficient access of people with disabilities.

9. **Simulation completed** – the report is generated from the simulation with all the choices made by the end-users/clients during the process. In other words, their feedback is composed in the form of saved screenshots (jpg), videos (the game's screen is recorded), audio, and word documents (depending on commenting choice). Furthermore, the participants answer the new questionnaire about spatial learning outcomes and their experience. The questions are used to assess the final input from the end-users/clients.

10. **Implement the changes** – The questionnaires before and after the user involvement are evaluated. It is a method to provide an overview of what the participants had learned, what they experienced, and how their input can improve design solutions. The designers use the received output from the simulation as a reference to make the adjustments to the final project proposal. BIM 3D models are modified and optimized following the end-users'/clients' assessments.

5.6. Paper prototyping

The application solution is aimed to be introduced to three types of devices: an immersive environment of Virtual Reality using the headset and controllers, Desktop view (online and as standalone pc app) with navigation by a keyboard, a mouse, or touchscreen, and finally, for mobile phone devices. The game's proposed levels start with the text representation on the screen, indicating all the tasks that need to be completed by a participant of the simulation.

The description of each assignment in the scenarios is both displayed upon hovering the cursor on the corresponding activity and as a pre-recorded audio annotation. After pressing or pointing with VR controllers at the "OK" button, a user is teleported to the starting point. The menu panel presents a list of the tasks, timer (for data collection), "Snapshot" (that can be used to save a screen at any point), the "Hide" button, "Design" (with displayed features), "Submit" (for completing the task and sending the feedback) and "More options."

It is possible to switch between different perspective options – 1st person or 3rd person of navigating a character using the "P" button on the keyboard or by the joystick button. Additionally, it is possible to change the navigation mode from walking to flying using the buttons G and F on the keyboard.

[B7.1 – B7.4] are reference points found in the storyboards, and work models presented previously in the report in sub-chapters [5.4. Storyboarding & 5.5. User Environment design].

Scenario [B7.1] Functionality of the rooms checker

The purpose is to supply the designers with insight from the end-users to create the most suitable and functional environment for their daily work and duties.

Find and design a room – *"Task 1. Find office room number X on the 3rd floor of the university, space is indicated with a letter A on the door. If you cannot find the space, press the "teleport" button on the screen. Subsequently, design the interior according to your wishes. Press "M" on a keyboard or action button B on the joystick to display the menu with the command "Design." It will show you features such as furniture 3D objects, colors, and textures. After you are satisfied with your design, press "Submit" on the menu where you can add comments as a text or audio, and highlight any problematic area of your concern, if any."*

A user starts in front of the entrance of the building. The location (underlined) in the description above can differ depending on the designers' choice for a space to be investigated by end-users.

Objectives of the task: Users, who are not familiar with the building's layout, are asked to find a specific place. The step indicates how easy it is to locate the potential space they may occupy in the future. On the way, the participant may notice some unpractical solutions that may require further considerations by the architects. Moreover, the end-users can present their wishes for the interior design while checking the space's functionality, if it is, for instance, too small, too dark, or if the location in the building is not suitable. The designers can potentially learn something new about the intended users that they have not taken into account before. It can help the investigate what is needed for the spaces to be more functional.

Rearrange the furniture to fit your working environment – *"Task 2. Compare your design solution with three prepared alternative proposals for the same type of space and rate the designs from 1 to 4 in order from the most functional design to the most unfunctional. You can find the rooms next to space you have just designed. They are highlighted with letters B, C, D on the corresponding doors, whereas your proposal is A. You can also press the "Inspirations" buttons to teleport between the design proposals. If you wish, rearrange the furniture again in your design proposal after examination of the alternative options. Add your comments upon pressing "Submit" in the menu where you will be indicating the rating."*

When completing the first task, the user is teleported to the hallway where they can see the doors to all the rooms. *Figure 21* shows the paper-prototyping system of this specific task. The "*Inspiration*" button is visible with the different proposals where the users can maneuver between them to provide feedback about the most suitable solutions following their wishes.

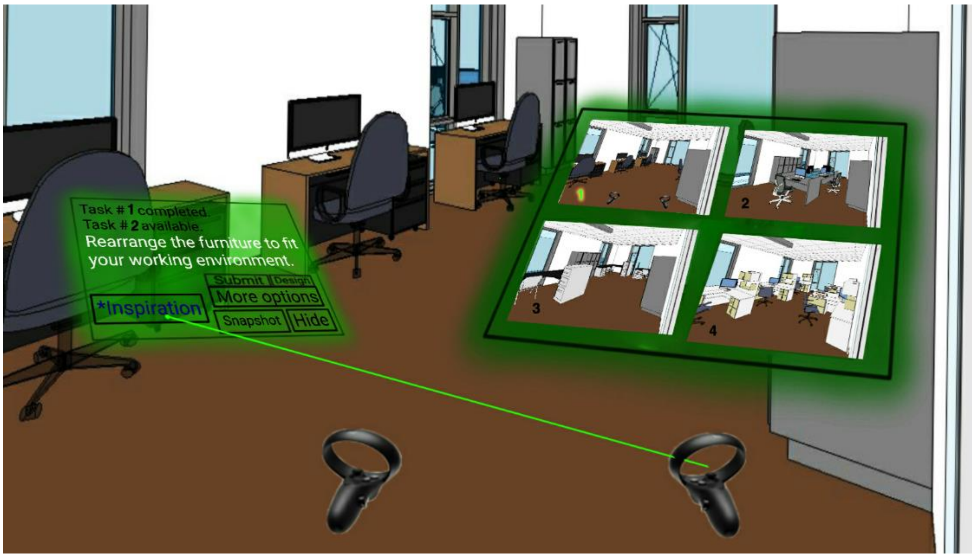


Figure 21 - Paper prototyping

Objectives of the task: The assignment allows end-users to see alternative solutions to the proposal they have just designed. They may discover more suitable or functional components to space, and upon the rating, they can indicate what they liked about specific solutions and give feedback on combining different concepts. Therefore, the designers can narrow down the ideas into the final design of the room.

Collaboration – "*Task 3. Collaborate with another user to design together* **______****. Use the "Design" command in the menu for the features. Discuss solutions between each other and submit the proposal with the "Submit" button. Add comments, highlight any area of your concern*."

* For example, one of the following options: a meeting room, a common room, a hallway, or a lecture hall. It is up to designers to decide the space to be investigated by the end-users.

The users start in the destined space for close collaboration. The participants can either work on the same device (desktop mode) or communicate with each other through the multiplayer option.

Objectives of the task: Similarly to *Task 1*, the output about space functionality and design proposition is gathered for the designers to consider while developing the final solutions. On top of that, two users' perspectives are formed into one result during the collaboration process.

Rate functionality – "*Task 4. Walk freely around the building or the room of your choice, and use light, day-night, weather features in the "More options" command found in the menu display. Then press "Submit" and send your comments*."

The users are placed again in the hallway and start investigating lighting and shadowing in the building upon choosing different settings.

Objectives of the task: The insight about the lighting solution is gathered to assess the functionality that may lead to changes in windows following the end-users' needs.

Scenario [B7.2] Accessibility of the rooms checker

The purpose is to supply the designers with the end-users' input to provide the design solution for an effective and accessible environment. (*See Figure 22*)

Walkthrough the building – "*Task 1. Walk freely through the building for 5 mins. Rate the walking paths – corridors, halls, and open spaces from a scale of 1 to 5 being the ideal connecting path. Use the "Screenshot" button for any area of your concern. When using the "Submit" command in the menu, upload comments via text or audio. Describe your experience."*

The users start in front of the building.

Objectives of the task: The designers can gather general comments and insights from the end-users during the building's investigation without restriction on where to go or not go. Rating of the visited spaces provides data collection that further indicates what rooms may need more consideration before submitting the project's final design proposal.

Follow the route – "*Task 2. Follow the predefined walkthrough path by walking, turning your head around, by a joystick to point for teleportation to the desired point in front of you, or using a keyboard when in the desktop viewing mode. Is access practical? Press "Submit" in the menu while rating your experience from 1 to 5 and providing feedback.."*

The users start in front of the building. Green arrows indicate the directions of the predefined route.

Objectives of the task: This assignment allows the designers to choose the specific route for the end-users to explore. It provides the input needed for spaces that require additional assessment of the needs.

Open doors and windows. – "*Task 3. Go to any rooms of your choice, open different doors and windows – at least 5 of each opening. Comment on the placement of the window/door, the direction of the opening, and size. In the case of negative feedback, please take a screenshot of the specific door/window. Press "Submit" on the menu*."

The users start in the big open space – hallway.

Objectives of the task: The study's goal is to design the most suitable solutions for the openings in the building. It allows the designers to adjust the opening direction, sizes, and shapes of the doors and windows ideal for the end-users' work.

Find the common areas/rooms – "*Task 4. You are asked to examine the locations of the common areas: _____*. Use the displayed dialog boxes to teleport to the spaces in question if you cannot find them yourself, walk inside and outside around the room to see what is nearby. Judge and rate the access to the locations. Press "Submit" when you are ready to provide feedback. Suggest a new location if you disagree with the proposed solution*."

*Common areas such as, for instance, toilets, printing rooms, laboratory, kitchen, hallways.

The users will be teleported to the requested room upon using displayed diagram boxes on the screen. The doors to the spaces in question are highlighted on the screen.

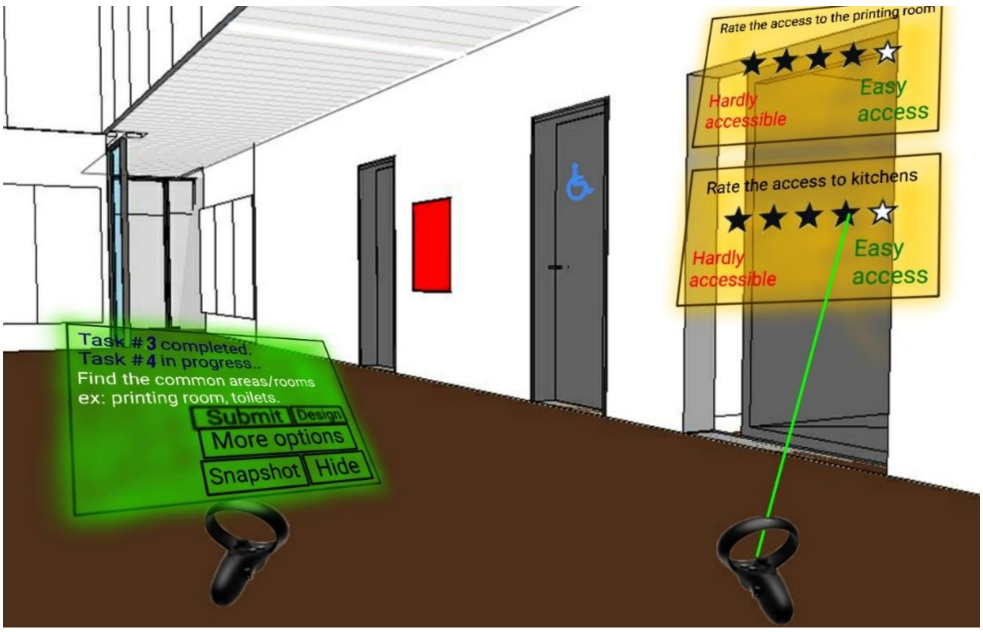


Figure 22 - Paper prototyping

Objectives of the task: The ideal placements are examined of the strategic rooms that the end-users visit daily during their stay and work in the building. It minimalizes risks of the unpractical solutions for locations of the spaces, such as toilets, printing rooms, laboratory or kitchens, and the proposals that might have been overlooked initially.

Scenario [B7.3] Accessibility checker for persons in a wheelchair

The purpose is to help the designers in the assessment of the accessible environment in the building for people of special needs in a wheelchair. Similar to the previous scenarios, users can change the perspective mode (1st, 3rd person). However, this time the wheelchair is visible. (*See Figure 23*)

Move around the building – "*Task 1. Move freely through the building for 5 mins. Rate the walking paths – corridors, halls, and open spaces from a scale of 1 to 5 being the ideal connecting path. Use the "Screenshot" button for any area of your concern. When using the "Submit" command in the menu, upload comments via text or audio. Describe your experience."*

The users start in front of the building.

Check if the toilets are handicap friendly – *"Task 2. Look around the surroundings. Access the toilet in front of you, highlighted with the arrow. Check the fixtures' layout inside. Is there enough space? Press "Submit" on the menu when you are ready with your feedback. Comment on design and access."*

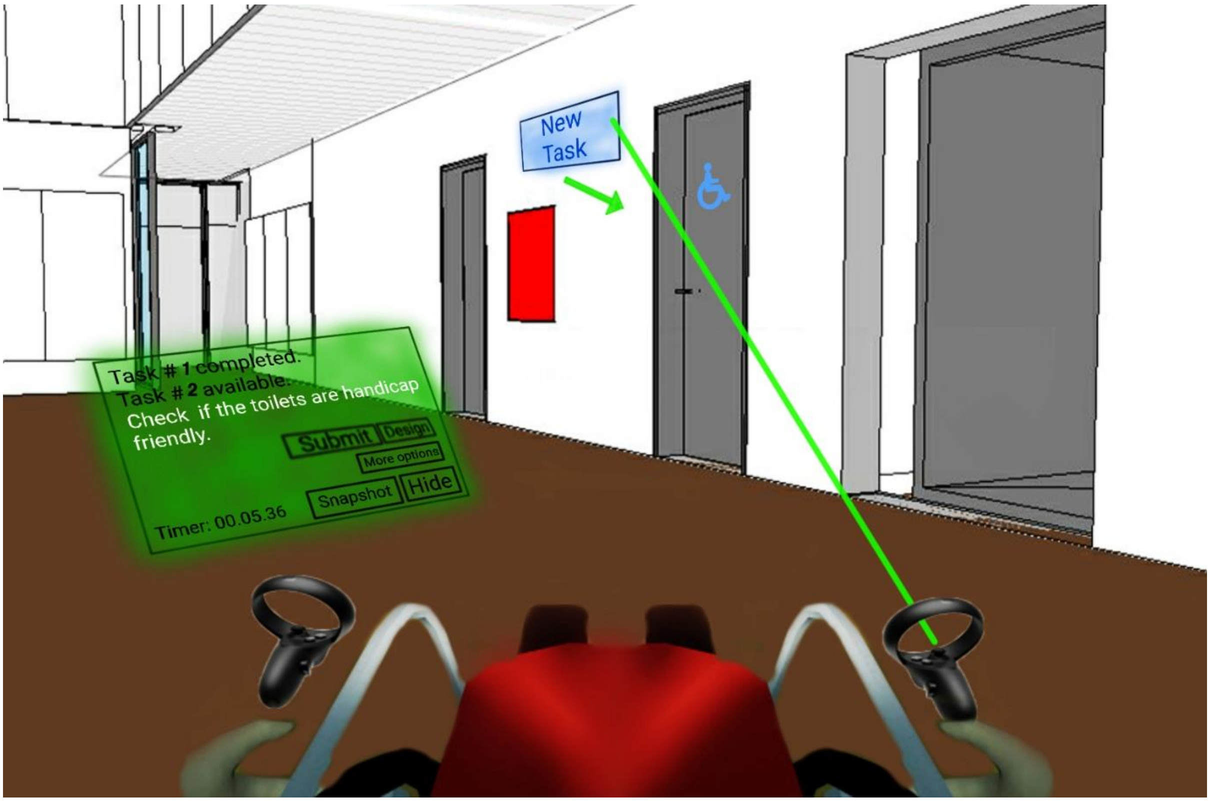


Figure 23 - Paper prototyping

The users start in front of the toilet for disabled people.

Follow the path - “*Task 3. Follow the predefined walkthrough path, by moving on the animated wheelchair, turning your head around, by a joystick to point for teleportation to the desired point in front of you, or using a keyboard when in the desktop viewing mode. Is access practical? Press “Submit” in the menu while rating your experience from 1 to 5 and providing feedback.”*

The users start in front of the building. Green arrows indicate the directions of the predefined route.

Objectives of the Scenario [B7.3] Accessibility checker for persons in a wheelchair: On top of the input gathered from the previous scenario about accessibility, this scenario provides necessary insights for the end-users of the special needs. The assignment examines the difficulties and ease of access for all the strategic areas that may need additional consideration to provide the most suitable solutions.

Scenario [B7.4] Emergency evacuation path checker

The purpose is to supply the designers with the users’ input for creating a safe and easily accessible environment in the building. During these assignments, either fire animations or damages resulted from the earthquake are presented. There are computer-generated characters that may or may not follow the right evacuation paths. (*See Figure 24)*

Find the fastest route and escape from the building (with the help of arrows) – “*Task 1. Follow the shown path by the arrows. Try to remember as many details as possible. When you exit the building, press “Submit” on the menu to stop the timer and proceed to the next task. Provide your feedback as either text or audio representation.*”

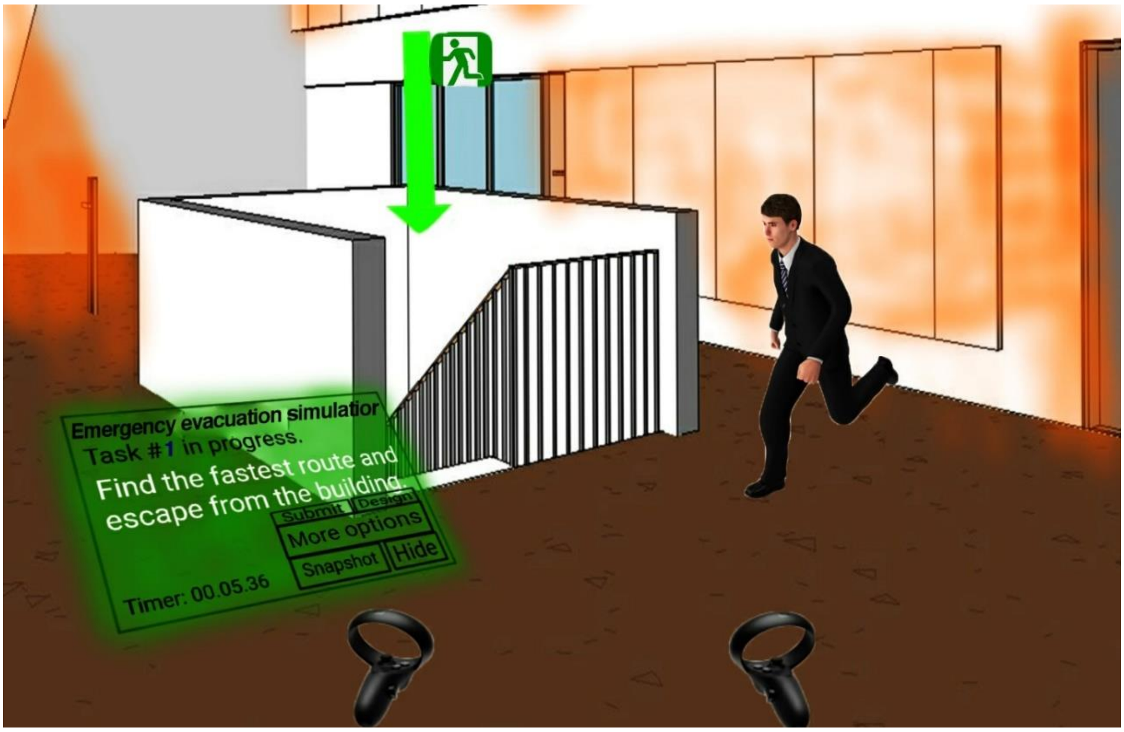


Figure 24 - Paper prototyping

The users are placed in a room chosen by the designers. Green arrows are displayed to guide the participants.

Find the fastest route and escape from the building (without the help of arrows) – "*Task 2. Escape the building. Watch for emergency signs for help. When you exit the building, press "Submit" in the menu to stop the timer and proceed to the next task. Provide your feedback as either text or audio representation."*

The users are located in the same spot as in task 1. However, this time they do not have additional help from the displayed arrows.

Find the firefighting equipment – *"Task 3. Find the firefighting equipment close to you. Watch for emergency signs that can help you locate the gear against fire. When you complete the task, press "Submit" in the menu to stop the timer and proceed to the next task. Provide your feedback as either text or audio representation*".

The users are placed in a room chosen by the designers.

Find an alternative escape solution - "*Task 4. Escape the building. Watch for emergency signs for help. Be aware some of the routes may not be accessible anymore. When you exit the building, press "Submit" in the menu to stop the timer and proceed to the next task. Provide your feedback as either text or audio representation."*

The users are placed in a room chosen by the designers. Some of the routes the participants are already familiar with are not accessible. The end-users need to find an available and safe way without any help to exit the building.

***Objectives of the Scenario [B7.4] Emergency evacuation simulator*:** The scenario aims to assess the environment's safety in case of emergencies such as fire or earthquake. The building's immersive representation can help the end-users learn faster about the necessary measures to find the fastest routes, escape, or find the firefighting equipment when they are not familiar with the building. Moreover, the designers may need to implement more effective solutions to the layouts based on the simulation outcomes.

Paper Prototyping testing with the participants having a background in the AEC industry.

After finishing the paper prototyping, a small presentation was sent to four Building Informatics Students from Aalborg University (Participant #1, #2, #3, #4) and to four professionals from the AEC industry (Participant #5, #6, #7, #8) to ask them for feedback and opinion on improvements. There were eight participants in total in the paper prototyping process. Additionally, afterward, the project was explained during an online student seminar.

Overall, the people working in the AEC industry and the Aalborg University students had positive feedback about the Virtual Reality paper prototyping presented. (**Participant #1** "*I think the process speaks for itself*"; **Participant #2** "*I like the idea of simulating the mentioned scenarios as everyone can imagine and play out different scenarios. It also seems like it will act as a good collaboration tool between the stakeholders*."; **Participant #4** "*I agree with the process, features, and scenarios. I think it could be useful for end-users and clients so they could understand the design proposals better*.") They also expressed input for optimizing and improving the development of the prototype. The paper prototyping idea was to test it before coding, so all the feedback improvements were welcomed. (*Presentation found in Appendix F*)

Improvements for the development of the prototype:

The user-interface needs to be as easy to use as possible because end-users might not be familiar with how VR works. On top of that, an instructive introduction should be held before the designers involve them in the simulation. (**Participant #1** stated that end-users would need to undergo training before using VR as it could impact their feedback.)

Participant #2 suggested a screenshot with comments as a feature of the prototype. In contrast, **Participant #3** expressed a need to show an overview table to the end-users before and after completing each task. Hence, they could know what is expected of them to do and how the end-users can achieve certain activities. Moreover, he added that they could be asked to evaluate the prototype's method at the end of the process and asked in-depth about the experience. **Participants #5** and **#6** added that screen recorder features and collision detection could be implemented.

Participant #7 said that the resources should be considered as everything takes time and money. Therefore, she suggested prioritizing accessibility and safety aspects because their ROI (Return on investment) is tangible and potentially attractive to investors. Participant #7 also pointed out that the proposed simulation could validate the stakeholders' wishes and that they should be involved as early as possible should be as early as possible. She suggested the following process (about User Environment Design): "*initial consultation with stakeholders, drafts (creation of 3D models), follow-up consultation with stakeholders, simulation processes, adjustments"* **Participant #8** advised to create a library with available types of furniture for the functionality checker to evaluate design options. He also suggested mapping data about where users go in the model for assessing the fastest routes with signage and color interaction.

As a next step, the changes implemented would have to be tested repeatedly until the prototype is optimized on paper, but giving the time-frame of this report, the feedback, and improvements from the testers, will be implemented in the next chapter, Prototyping.

Chapter 6. Prototyping

The prototyping phase demonstrates the steps required to send the BIM model to a game engine and start working on possible features, scenarios, and mechanisms to enhance improved communication and collaboration with the end-users and clients. The goal is to present design proposals and receive necessary input from people acting as the building's intended occupants to prepare effective architectural solutions. Chapter 6. Prototyping follows the guidelines and commentary gathered from the previous chapter to test the prototype.

For the prototyping, the Revit model of the newest building from Aalborg University is used as a case project. The building's total area is – 8.978 m², and it is split into six floors (basement, ground, first, second, third, and fourth floor). The prototype is also referred to as a simulation, serious game, and game throughout the chapter.

The process in the chapter starts from step 4 Exporting for creating a simulation demonstrated in the subchapter User Design Environment of Chapter 5 Design of the Prototype - when the BIM model is prepared with LOD 300.

Autodesk Revit 2020 and 3Ds Max 2020 are the primary programs used to show the principles needed to be considered to import the model to Unity 3D successfully.

6.1 Export to a game engine (Unity3D)

For the comparison purpose, two copies of the same model were added to Unity3D. (*Figure 25*) The building on the left represents the result of using 3Ds Max as the link between Revit and Unity, and the model on the right was imported directly as FBX from Revit. It shows that the game engine cannot display the materials without extension plug-ins or adjustments in 3Ds Max. (*Appendix C* consists of detailed steps of exporting the FBX file to Unity via 3Ds Max, and the descriptions of the alternative solutions can be found in the chapter literature review)

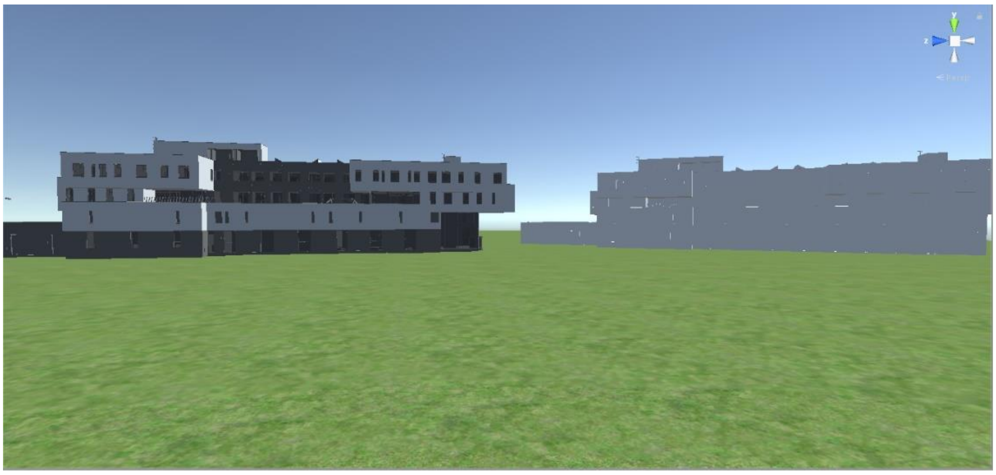


Figure 25 - The imported models in Unity 3D, an optimized model with 3Ds Max (left) and imported directly from Revit as FBX (right).

On top of that, for levels 4-7 of the game, Twinmotion 2020 was used to export models to the game engine.

6.2. Development of the prototype

The prototype was developed in the game engine Unity after exporting and preparing the BIM model file from 3D modeling software. The process was centered around implementing ideas and outcomes from the previous chapter – Design of the Prototype. The goal is to add together scenarios from four categories previously constructed into an immersive simulation that can be used for designers in architectural firms to test with end-users (including clients and/or their representatives).

- *Scenario [B7.1] Functionality of the rooms checker*
- *Scenario [B7.2] Accessibility of the rooms checker*
- *Scenario [B7.3] Accessibility checker for persons in a wheelchair*
- *Scenario [B7.4] Emergency evacuation path checker*

The simulation acts as the communication and collaboration central point to extract knowledge from the building's future occupants. In other words, the objectives stated throughout [5.6. Paper prototyping] subchapter, are core focus to be fulfilled to answer the master thesis problematic theme.

Figure 26 shows a simple menu as a starting scene for the simulation. This interactive simulation consists of seven levels based on received feedback and concepts from Paper Prototyping descriptions of the tasks. Three game builds are considered for interactions with the end-users – **Desktop mode view** (as a standalone app on PC), **Web-based** (designers can send an online link to the participants if they cannot be present in person), and for **VR headset** to navigate with controllers.

Figure 26 Menu interface of the simulation

Workflow to create a simulation for involving end-users in the designing process

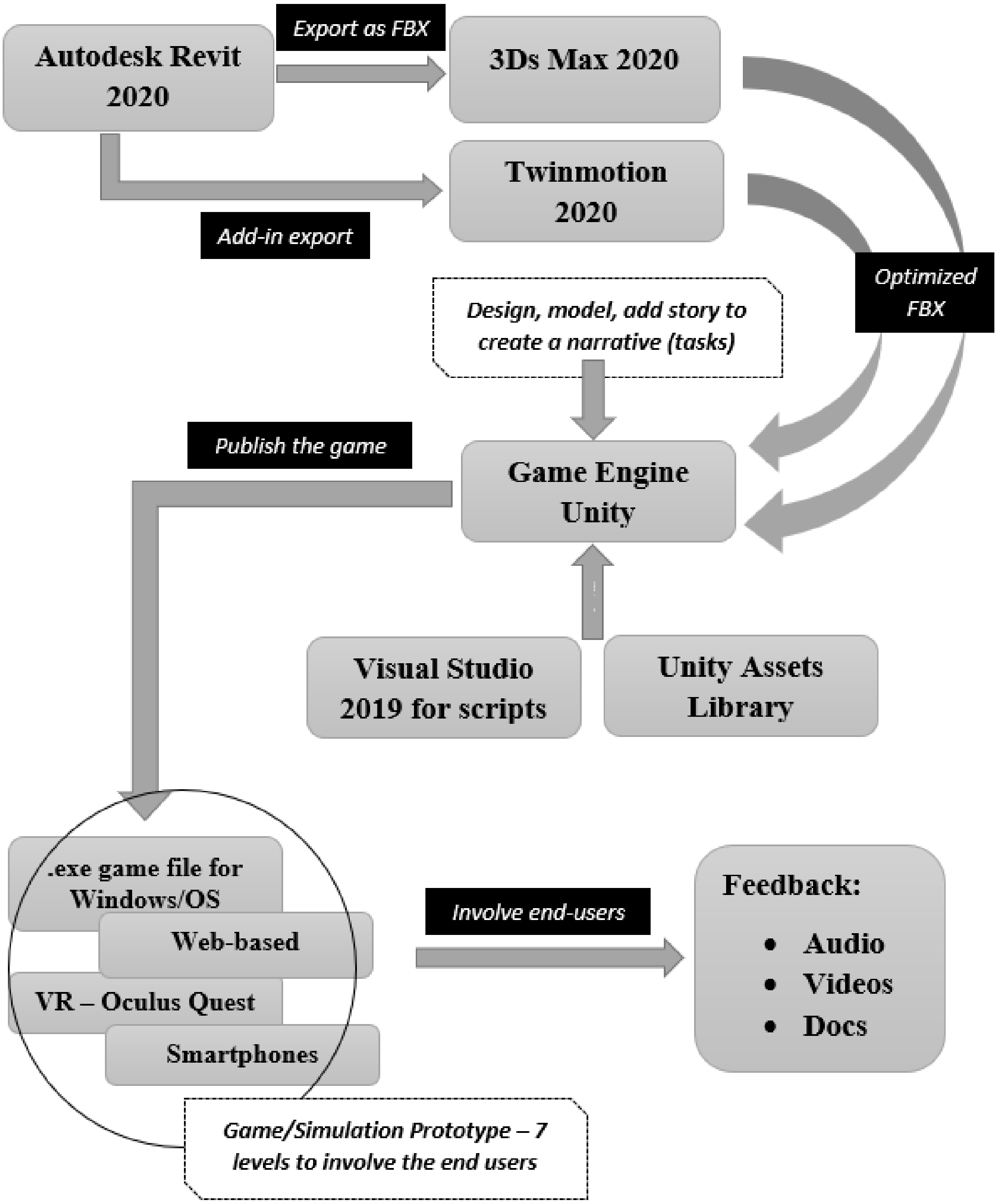


Figure 27 - Workflow to develop an immersive and interactive simulation

Figure 27 describes the workflow of procedures chosen for developing a working serious game. The next subchapter provides descriptions of the programs and hardware utilized for the prototype.

Apparatus employed

Revit 2020 - For the project, the .rvt file (Autodesk Revit Project) with the BIM model was received. It consisted of the university building representation for the department of the built environment. Both authors have been familiar with this 3D modeling software for BIM. Therefore, the initial work took place in Revit. The model was prepared for export in 3D view, and to make sure the rooms, which the end-users were supposed to check, are visually ready, the model was checked with 3D walkthroughs and renderings. Additional layers, materials, textures, and furniture were added while unnecessary data was removed (lines, annotations, redundant fixtures, objects). For example, different types of furniture with high-quality textures were placed for lobbies, study rooms, lecture halls, toilets, and offices – investigated areas of the game scenarios. The aim was to assemble a practical and realistic game that could be presentable to clients/end-users.

After importing the FBX file to **3Ds Max 2020**, the digital building was further optimized to maintain its graphical layers for export to the game engine. Every object was intended to be a separate entity and not grouped by material or type (export as “Do Not Combine Entities”). Individual items were more suitable in unity for developing the designing tasks (e.g., changing textures, moving separate entities, animating doors). Chosen modeling software is discussed in the literature review [3.3.2. BIM software and animations tools]. Moreover, 3Ds Max was mentioned by many reviewed professional publications as an optimization medium between Revit and game engines, and during testing for the project, it was found as a suitable choice for the preparation and the model’s export.

Twinmotion 2020 – as an alternative export method, this direct, free plug-in solution was appointed for the project. (Plug-in explained in [3.3.3. Export from Autodesk Revit to Unity Gaming Engine]) High-quality models, easy to use (just one click in Revit) for creating FBX file, and swift process were the reasons for including this procedure in developing the serious game. However, the issue appeared while trying to export each element as a separate entity - some objects were missing their textures after importing to a game engine; thus, it would require a bit of manual work. Therefore, the 3Ds Max approach was kept for the first three levels of the game that needed designing tasks on the individual elements, while Twinmotion was used for levels 4-7 of the game where the model’s objects could be grouped by Revit family type.

Game Engine Unity 2019.4.9f1 – upon testing individual game engines (Unreal, CryENGINE, Unity as the most popular) that could be employed for the project, the choices fell on Unity. Technical performance indicators appeared to be enough; the game engine is connected to a large community, provides numerous tutorials, a friendly, easy-to-use user interface, and a rich library of available assets for game content creation. These aspects were necessary for the software choice because neither of the authors had any knowledge about game engines before starting the project research. Moreover, Unity was utilized in most of the solutions for the AEC, Facility, and Operation, reviewed in chapters [3.3.4. Serious Gaming applications in the AEC industry; and 3.4.1.5. VR applications for the AEC industry].

Assets Unity Store – [184] provides resources both free and paid for adding features, objects, animation, and mechanics games development.

- Standard Assets – contains simple mechanisms and elements to begin with. First Person and Third Character Controller were implemented into the simulation. It allowed positioning the start-up point with the choice of the character. It was chosen to incorporate both navigations to test with the end-users. (Additionally, for one task, a wheelchair object was imported to act as a character for the First and Third-person camera.) Standard Assets' animation behaviors were utilized as a base for computer-generated users, non-playable characters (NPC).
- The Unity Multipurpose Avatar (UMA) system – offered customizable NPCs, and for levels 4-7 of the simulation, multiple NPSs were placed in the simulator. Their appearances were adjusted and set to be randomized.
- TimeOfDay&WeatherSystem – allowed the creation of changing day and night circle and weather features presented in level 3 of the game.
- Ambiens ArchToolkit – complex package assets that made it possible to animate doors in the model, for users to be able to open them upon interaction; simple user interface with control buttons, and enabled the development of texture changes, along with moving objects such as furniture.
- Various furniture packs were used, such as *Chalet style furniture*, *Furniture*, *Gray Furniture Pack*, *GameReadyAssets*, *Revolving Door*

Visual Studio Community 2019 – is a program directly incorporated into Unity, which allows creating scripts for simulation/game.

Revolving Door / DoorRotation – scripts for enabling animation of the automatic door at the entrance

Camera Switch – changing perspective between first and third-person characters.

StopWatch – script for programming timer inside the simulation with options start, stop, and reset.

Main Menu - enables interactive buttons in the menu to start the game and to quit when pressing corresponding fields. (*Figure 28)* The rest of the coding for the other scrips can be found in *Appendix G.*

```
using UnityEngine;
using UnityEngine.SceneManagement;

Unity Script | 0 references
public class MainMenu : MonoBehaviour {

    0 references
    public void PlayGame()
    {
        SceneManager.LoadScene(SceneManager.GetActiveScene().buildIndex + 1);
    }

    0 references
    public void QuitGame()
    {
        Debug.Log("QUIT!");
        Application.Quit();
    }
}
```

Figure 28 Script for interactive buttons in the Game's Menu

To Task2 – allows changing scene to the next one (from one level to the next)

TheWizardsCode – scripts in this package were used for random movement of the NPCs on the chosen paths inside and outside the building [185] & [186]

WebGL – is an available build option (*Figure 30*) in the game engine that makes it possible to view a game online. It is important to make sure the file is as small as possible with easy controls to enable users to play it even when they have slow internet speed. *Figure 29* shows the intended platform choice and content to be published (scenes of the game). It can be built for Unity website, or alternatively, for hosts such as itch.io; simmer.io; Microsoft Azure, and GitHub. [187]

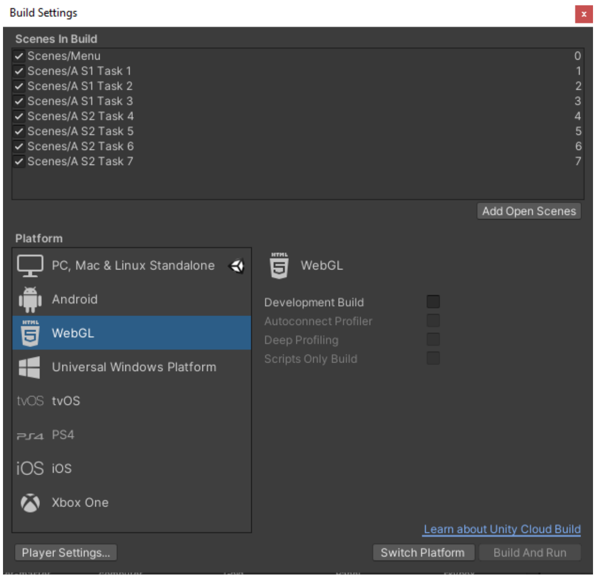


Figure 30 - Build settings in Unity

Figure 29 - Unity WebGL - game uploaded online using itch.io

Simlab Composer 10 / VR Viewer – based on the analyses of the VR software, Simlab provider was chosen to present some of the concepts essential for the end-users (designing, choosing furniture from the provided library, and annotation features)

Hardware, **Oculus Quest** (+ two controllers) is a standalone device that can be connected to a computer via USB Oculus Link to view directly progress in the Unity game engine or play the final product through cloud services wirelessly. (*Figure 31*)

Figure 31 - Hardware utilized for the project, laptop, Oculus Quest

6.2.1. Level 1: Find and examine study rooms in the university

The first level takes the participants to examine four different designing solutions for study rooms in the university – areas they occupy in the future. The end-users are placed in the virtual environment in front of the building, and there is a provided description of what they are specifically asked to do. *Figure 32* presents the view from the simulation after they press "*PLAY"* in the opening scene. It is possible to change between "*FLYCAM*" and "*WALKCAM*", according to the preferences of the participants.

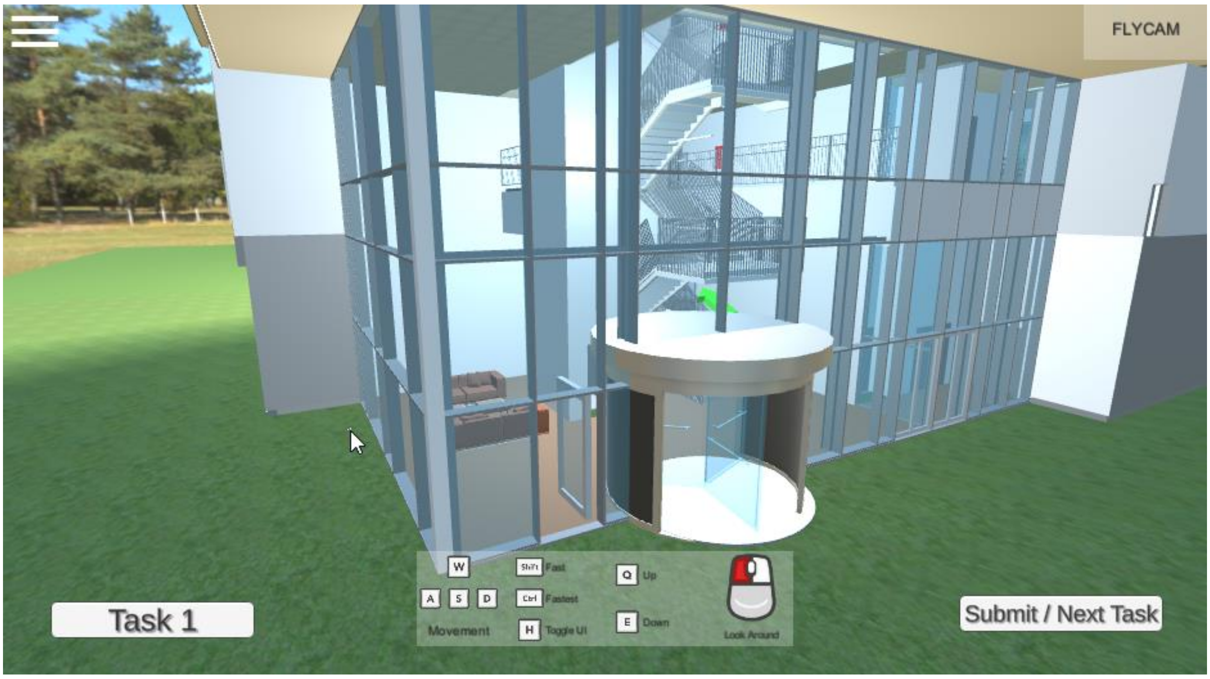


Figure 32 - Level 1 overview in the simulation

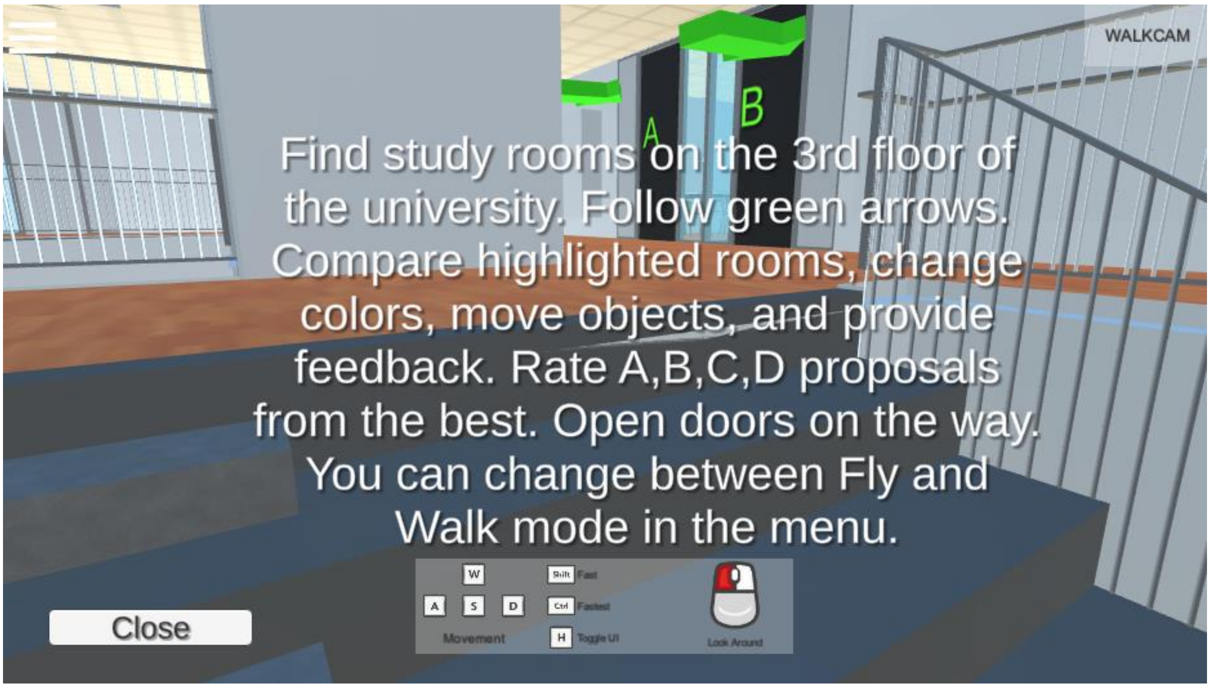


Figure 33 - After pressing the "Task 1" button

Each level of the immersive simulation has got two interactive buttons – "*Task 1*" (numbering changes with every scene, upon pressing it, the description of the task shows up) and "*Submit / Next Task*" (it takes users to another level). Moreover, the navigation panel is provided (for desktop and web-based mode). *Figure 33*, above shows the description display after the users press the "Task 1" button.

The level aims to provide the designers with essential intel to create the most suitable and functional spaces for the end-users. The participants are not familiar with the building. Thus, the first step in the simulation gives them an overview of the path they might follow during their everyday work to access the study rooms on the 3rd floor.

The outcomes may suggest that, for instance, the space is too small, or the furniture layouts are not practical. Therefore, it can help the designers adjust the proposals to make as functional rooms as possible. All the comments may provide new information about the building's future occupants and form good profiles with their wishes to consider when creating the final project development.

Figure 34 - 2nd floor of the university

While the participants follow the green arrows on the chosen route, they can look around to investigate everything that is on their path. *Figure 34* presents a screenshot of the 2nd floor in the university. The simulation can result in a better common understanding between the end-users and the designing team. The participants can interact with the surroundings in the model and express more effectively what they think.

The end-users can move furniture around and change materials, colors of objects, walls, or any other surface following their preferences. They are asked to rate the design proposals and provide feedback that can be essential for designers to create optimal solutions – a high-quality product. *Figures 35-38* illustrate four propositions of the study rooms that the participants must interact with within level 1.

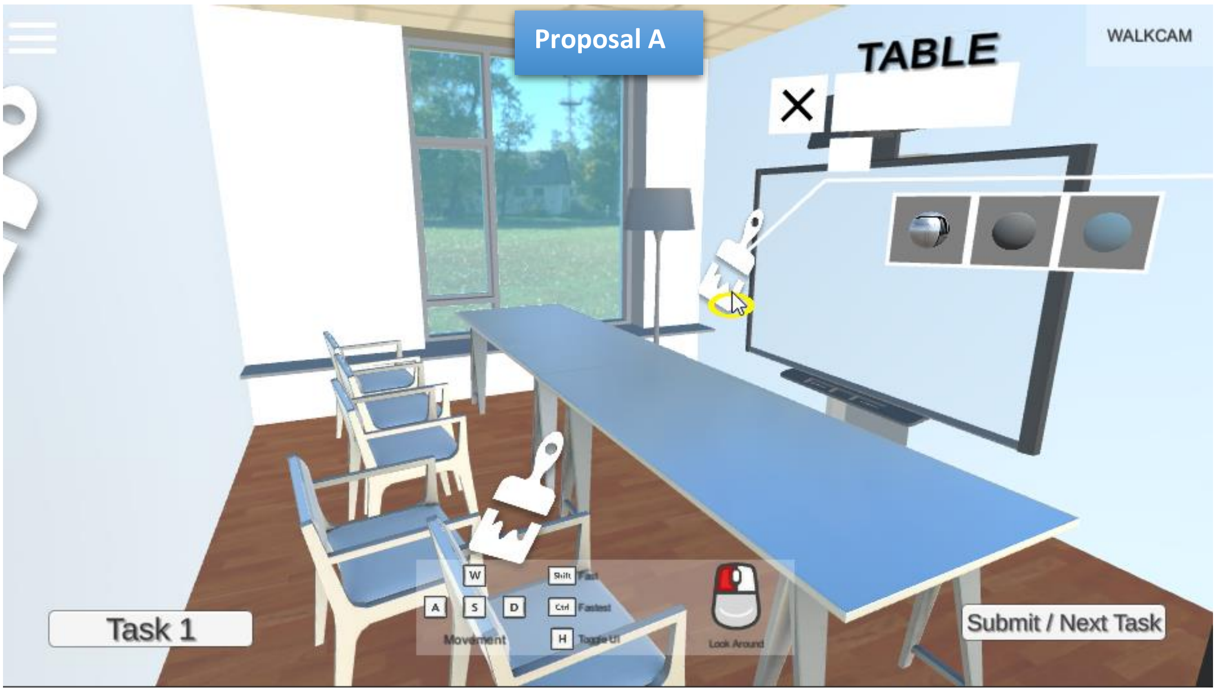


Figure 35 - Proposal A of a study room

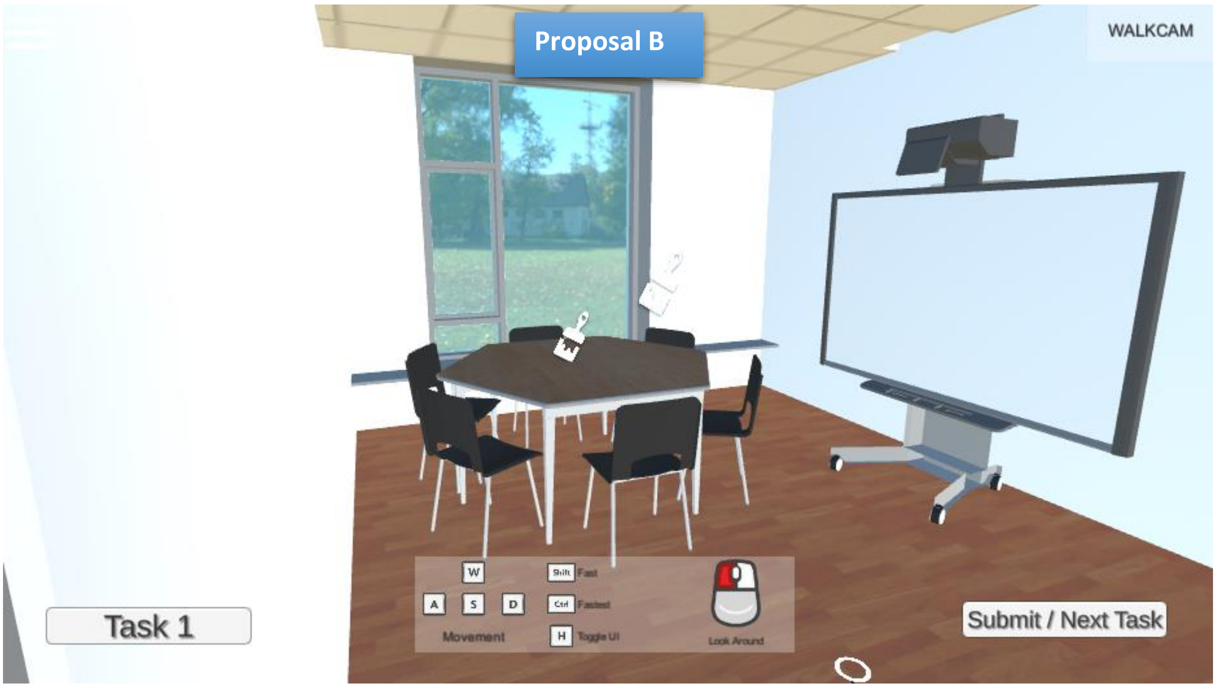


Figure 36 - Proposal B of a study room

Figure 37 - Proposal C of a study room

Figure 38 - Proposal D of a study room

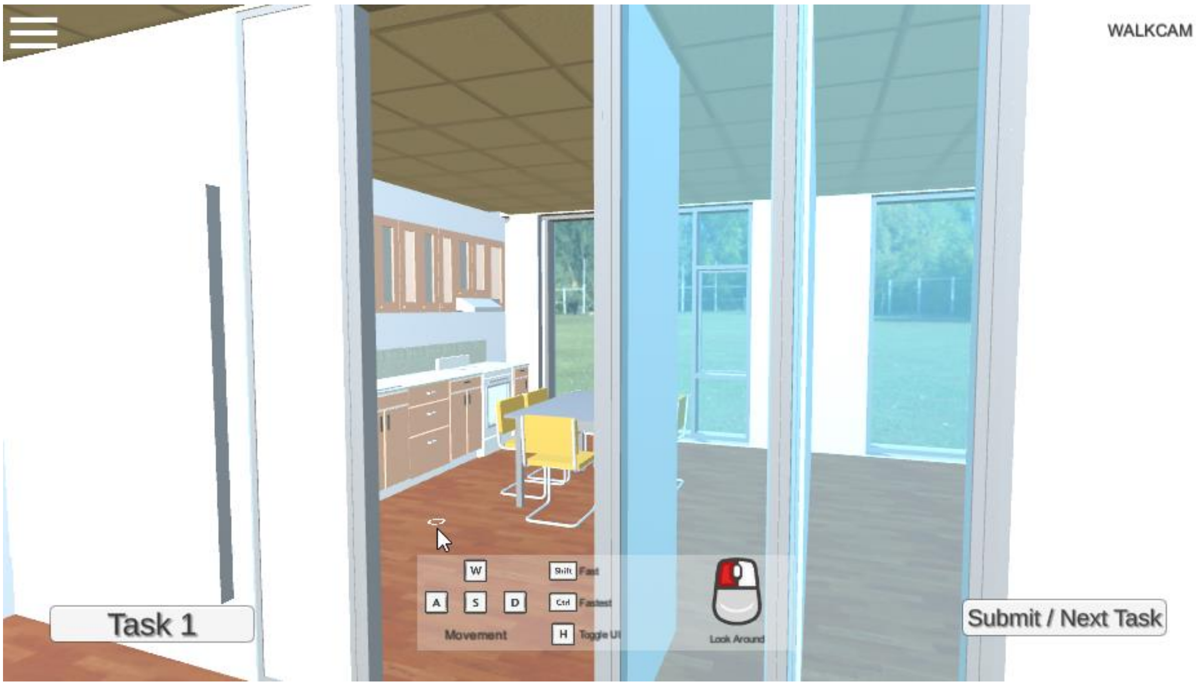


Figure 39 - Interaction with openings

This level also combines tasks of opening doors in the virtual environment. (*Figure 39*) The participants can judge the direction, size, and surface design of any opening in the building. Every element may affect the daily work at the new facility of every occupant; therefore, it is important to assess different solutions as early as possible in the design phases.

When the end-users are satisfied with the investigation and proposing their solutions to the design options, they are ready to move forward to the second task.

6.2.2. Level 2: Collaborate with another user to design one of the lecture halls

The second level is navigating towards extracting intel from end-users that are asked to work together to design one of the university's lecture halls. They are presented with different furniture proposals to enhance finding the most optimal and efficient solutions to satisfy the future occupants and designing team. The participants can change surfaces of the objects and interior design (walls, floors, doors, windows) and move around equipment. *Figure 40*, below illustrates the view from the simulation. Based on the literature review and results from the interviews, it is noted that every user may have different perspectives on their future workplace; therefore, the output is gathered as the outcome of the collaborative feedback.

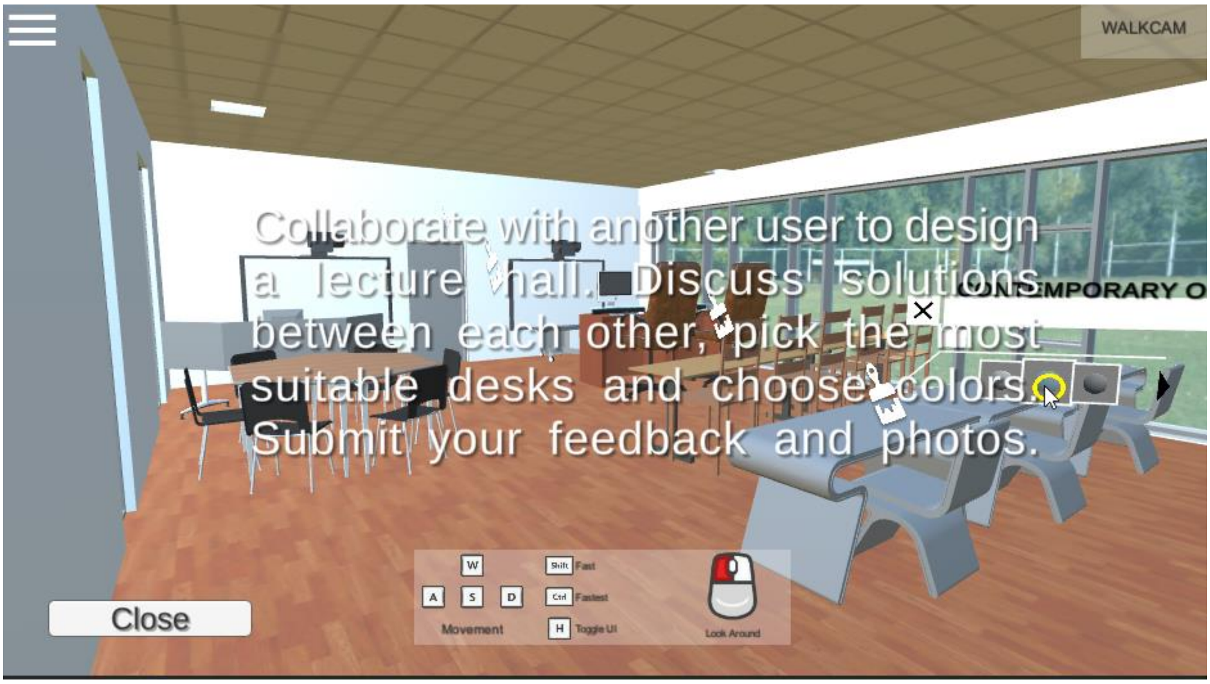


Figure 40 - Level 2 overview

6.2.3. Level 3: Examine the building based on changing lighting and weather features

After completing designing tasks, the end-users are taken to the lighting assessment level that changes throughout the day (*Figure 41).* Their feedback and screenshots of suspicious areas are used to support the most suitable adjustments of the space functionality. The weather factor is also applied - the participants can experience, for instance, raining and snowing, if and how it might affect proposed lighting and window design in the building. For this prototype, the accurate environment has not been created, being one of the limitations of this report, but for accurately experiencing how the environment affects the building, the surroundings should be as realistic as possible.

Figure 41 - Level 3 overview

6.2.4. Level 4: Walkthrough the test building

When the assessment of the space functionality is complete, the end-users are asked to investigate accessibility requirements inside the building. (*See Figure 42*) This time the level offers open tasks where the participants can walk freely and see any space of their choice. There are not any restrictions put in place on where to go or not to go. For a more immersive and realistic feeling, the NPCs (non-playable characters) were spread in the model. These impersonations of the real people were coded to walk and express animated behaviors. Therefore, the end-users can have close to the real experience as if the designed structure has already been built. The designers may receive some specific intel from this level about the spaces' requirements they have not considered before.

Figure 42 - Level 4 - walkthrough the university

6.2.5. Level 5: Follow the route and assess locations of the common areas

Level 5 is supplied with a controlled narrative to follow on top of the previous step. The designers can implement a guide for a specific path for the end-users to take, while at the same time, it can help with gathering feedback on the most problematic spaces where precise needs and preferences should be defined.

For this level (*Figure 43*), it was chosen to ask the participant to walk through the most busy floors of the building (1st, 2nd, 3rd floor), and on the way to stop for the checkpoints – toilets, printing rooms, kitchen, and laboratory. It provides the opportunity to receive information about accessibility to the common areas. Moreover, the end-users can judge the hallways and corridors that connected their path to the destination zones. The participants are free to propose different locations if they do not feel satisfied with the displayed solutions. The timer feature is available to extract data about how long it takes for the end-users to follow the route to the finish point.

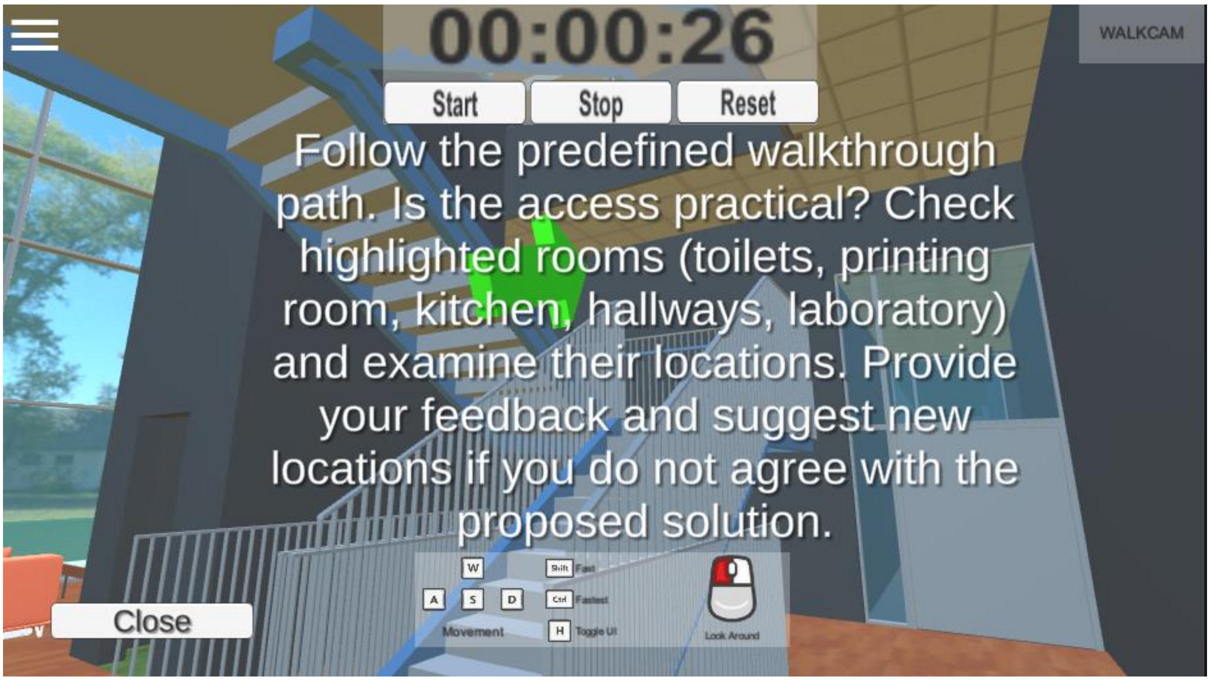


Figure 43 - Level 5 overview

Figure 44, below shows a checkpoint for assessing the toilet for persons with disabilities. The access is examined and fixtures layouts.

Figure 44 - Wheelchair access check task

Another feature of the simulation was designed to have a 3rd person character navigation (*Figure 45*). It can help with the assessment of the accessibility when entering a new room to investigate.

Figure 45 - 3rd person character task walkthrough

6.2.6. Level 6: Escape from the building with the help of arrows

The concept behind level 6 is to collect data about users' behaviors during emergencies. (*Figure 46*) For the simulation, in this case, – fire animation was incorporated into the virtual environment. The goal of these tasks is to escape the building as fast as possible while looking for the red boxes in the wall, where fire-fighting equipment is located. The end-users are guided with the help of the green arrows. Moreover, the timing informs the designers about how long the escape out of the building may take.

Figure 46 - Level 6 overview

The screenshot feature is presented in *Figure 47*. Throughout the simulation process, the participants can point out any area of their concern and refer to it during feedback.

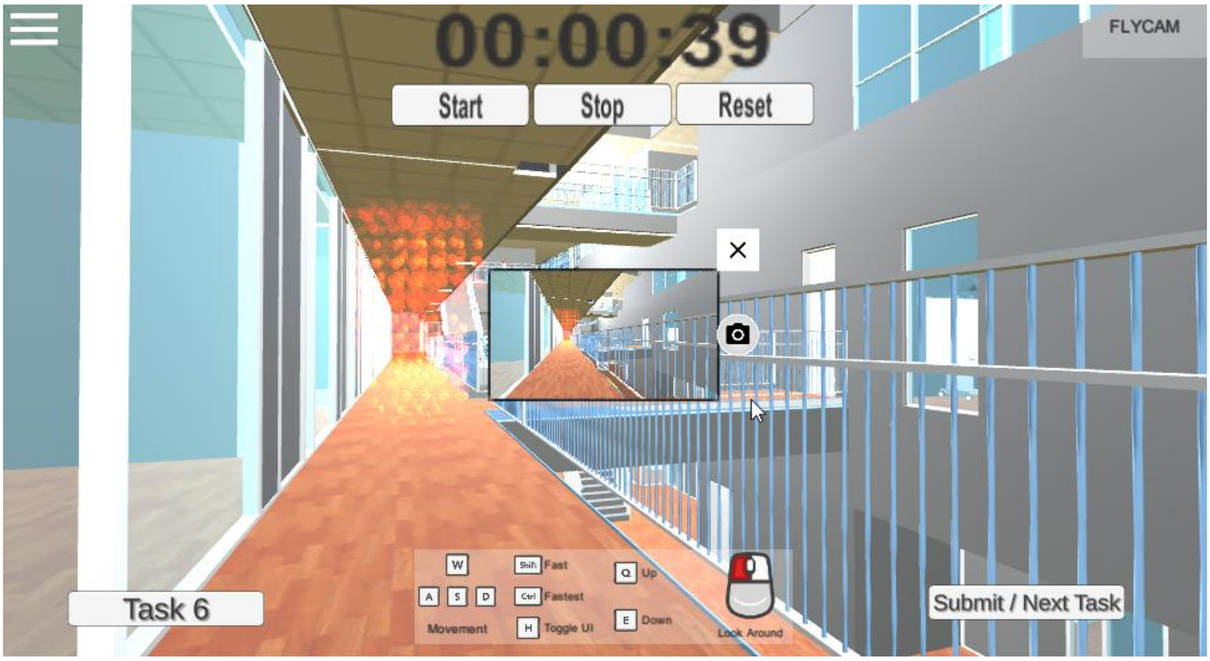


Figure 47 - Screenshot feature

The end-users can choose between different perspective options depending on their preferences. (*Figure 48*)

Figure 48 - 3rd person character in the fire escape level

6.2.7. Level 7: Find the fastest route and escape without the help of arrows

Level 7 takes the previous step even further. The previously learned escape route is now blocked, and the participants need to find an alternative route that is available to escape out of the building. (*Figures 49 and 50*) The simulation environment in level 7 can provide essential feedback if the users can find a quick way out of the university in case of emergency and if the previous levels were enough for them to learn about layouts.

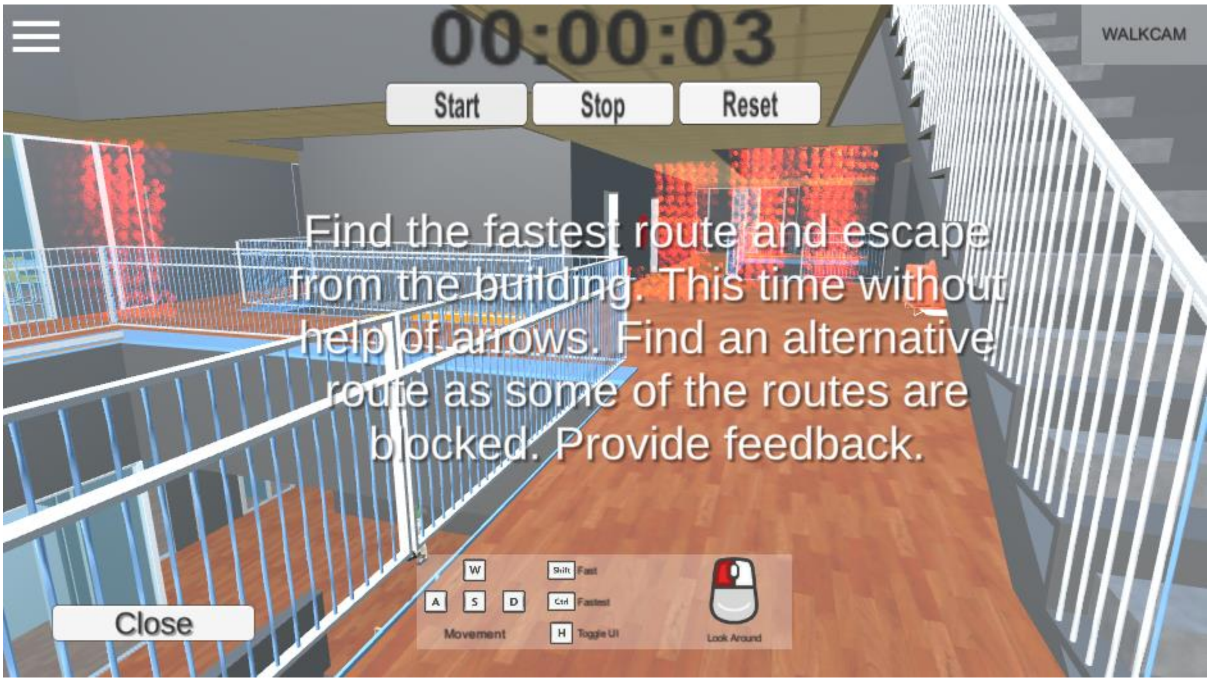


Figure 49 - Level 7 overview

Figure 50 - The blocked access to the previously followed route

6.2.8. Summary of the prototype development

The simulation was built as a standalone program to be played on the PC and was published online. Moreover, the game was made ready for VR viewing. On top of that, to present some of the designing features (adding furniture) and annotations for collaboration between the designing team and end-users, a simple simulation was complete using Simlab VR viewer. (*Figure 51*)

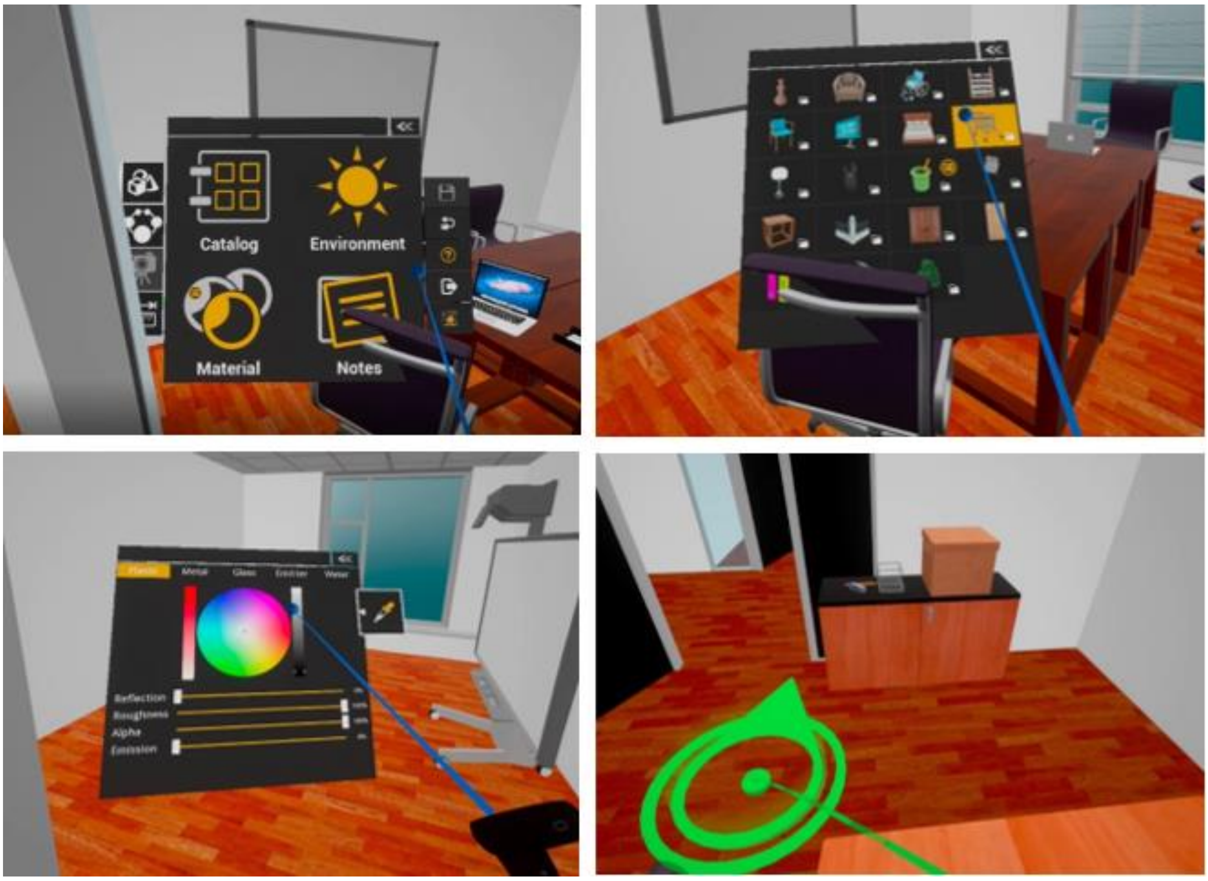


Figure 51 - VR testing in Simlab Viewer, library with furniture and collaboration features

The figure above demonstrates essential features that could be used on top of the presented prototype in the previous subchapter.

6.3. Data collection

Data collection while using the simulation prototype.

Before starting the simulation with the end-users/client, they are receiving a short introduction to the project and to the simulation to have an idea about what tasks they will have to perform. During the simulation, they will have to answer questions for each level to understand more in-depth what their requirements or wishes are from the new building. After the simulation, they can be asked questions about different focus areas they spent more time on.

These questions have to be created based on the type of building and its purpose, and for example for the test building used in this report, the questions were made accordingly. See *Appendix H* for the detailed testing process.

Another way of collecting data is by letting the end-users leave comments on particular objects or certain areas from the building, taking screenshots of specific areas, or even record quick messages to express their requirements/wishes. This way, a report can be generated at the end of the simulation session containing notes, screenshots for the design team to evaluate them. However, this report with annotations, screenshots, and recordings would require future development, but for testing in this report, we managed to implement the screenshotting feature (*see Figure 52*), and the annotation and recording options were tested by the users using Simlab Composer (*See Figure 53*).

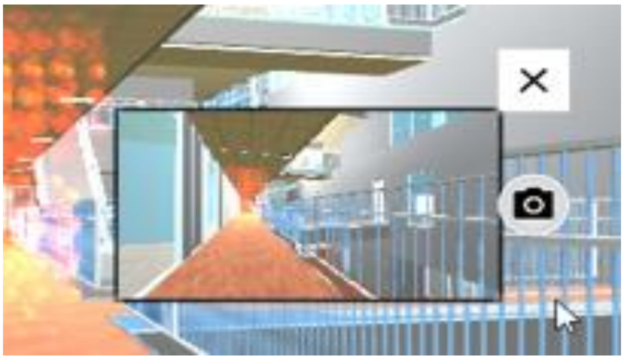


Figure 52 - Screenshot feature of the prototype

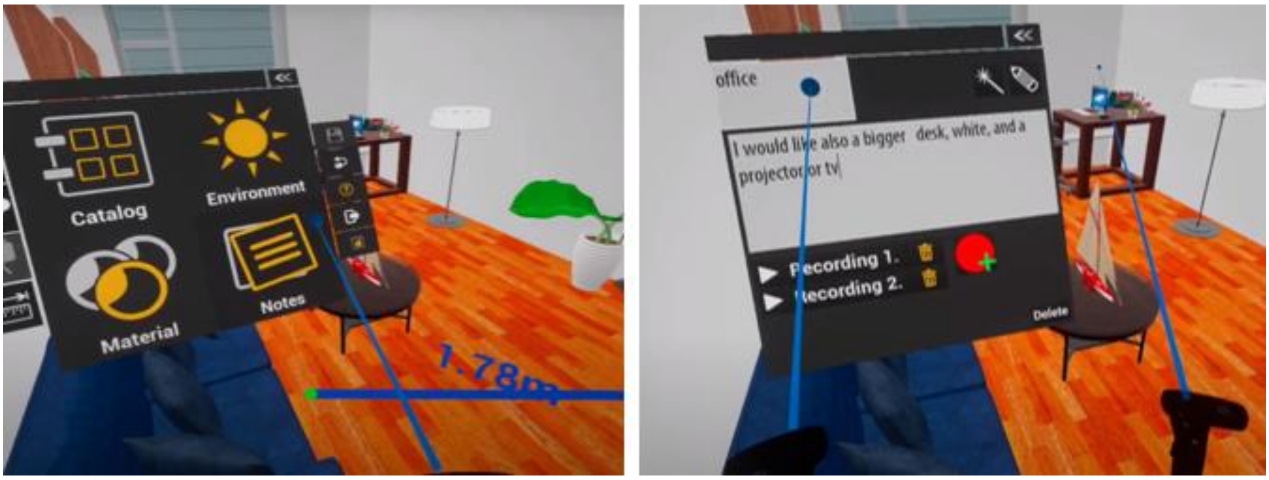


Figure 53 - Annotation and record message feature in Simlab Composer

All these features can be implemented in the actual prototype with a certain level of programming skills, then the designers can consider this input from the end-users or clients and adjust the design of the building accordingly, but let’s see how the information from the prototype can be automatically generated and how it can be used

Automated data export

This kind of data is automatically collected while the user is playing the serious game. Data is exported afterward in files, ready to be sent into a line renderer to create a user's path or generate a heatmap with all the essential points that received attention from the user. During the period of creating the prototype, in the end, we managed to export two sets of data out of the prototype after the participant has complete all the levels.

Figure 54 shows the export of two sets of coordinates, one with the player's position and one with the rotation coordinates saved for each frame. This can also be changed accordingly to save the coordinates per second or for every five seconds, depending on the purpose.

After the participant finished the simulation experience, this document is automatically generated with the date and time to track all the end-users who have tested the prototype. The script for exporting this information can be found in *Appendix I.*

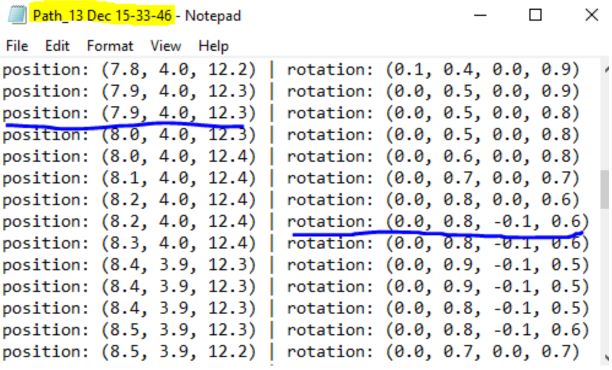


Figure 54 - Coordinates of the participant in VR

How to use these coordinates:

GPS tracking for generating a line path. In unity, there is an option to create a line path based on the coordinates you click on; this is for creating predefined paths for characters in a game. However, this tool can be used as a reverse process by sending a list of coordinates and generate a line path in the model.

A line path in the model as seen in *Figure 55* can be generated by pushing the list of **XYZ** coordinates into the line renderer option from unity to generate in 3D the path used by the participant to examine the model (for example, what path he used when there was a fire simulated). In this case, numerous paths can be generated in the model to observe what path most of the participants have used to escape and consider the escape routes.

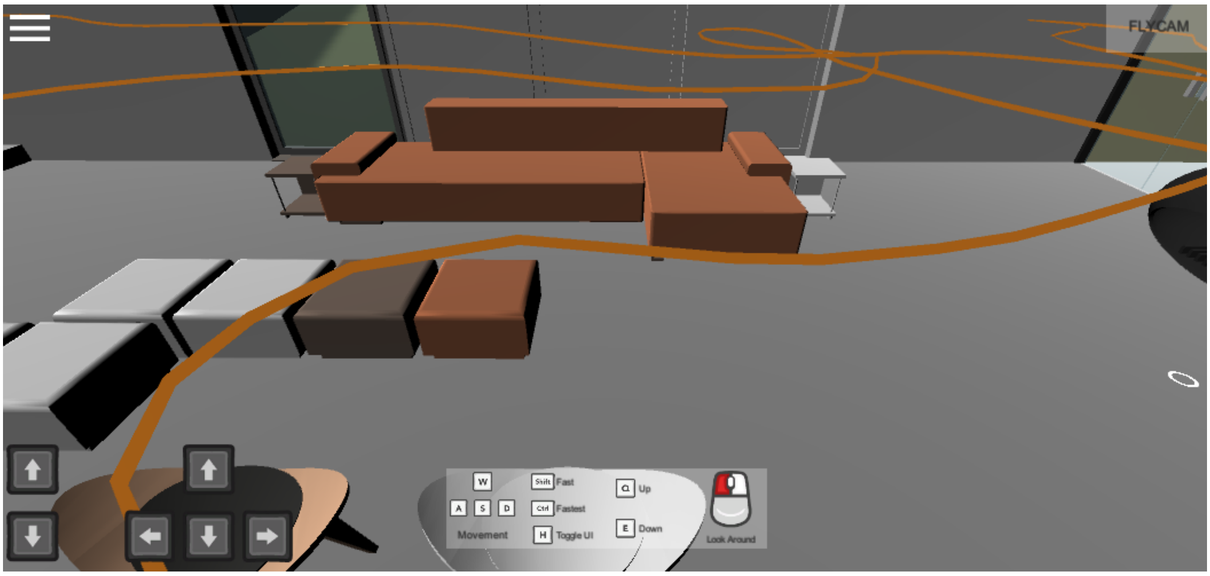


Figure 55 - Line renderer in Unity

Head rotation/orientation for creating a heatmap. The second column of coordinates is the camera's rotation, tracking where the participant is spending most of the time looking. Therefore, these coordinates can be used to create a so-called heatmap. These heat maps can, later on, be used, for example, to test if the emergency signs are placed correctly or even visible. Automated data export is also the function of the prototype that can be developed in the future.

The next subchapter presents the results from testing the prototype and the SimLab VR simulation, containing the requirements/wishes as input from the participants acting as end-users of the future building.

6.4. Results of testing the prototype with the end-users

The prototype's testing took place at the apartment of one of the authors of the report, with the participants from the table below, using the game described in this chapter. Each user spent approximately one hour for playing the game and providing feedback.

Test Participants		
	Occupation	**Equipment**
Participant 1	Architectural Technologist	Laptop + Oculus Quest
Participant 2	Architectural Technologist	
Participant 3	Student	
Participant 4	Student	
Participant 5	Student	
Participant 6	Student	

Table 11 - Participants in the testing

Before the testing, a set of questions have been addressed to the participants during and after the testing. The questions, together with all participants' answers, are found in *Appendix H* and were created based on the literature review and the interviews presented in chapter 5. The objectives of the testing are following the aims and objectives presented in this report's introduction.

The results from the testing are presented in the table below under the form of requirements/wishes and improvements/suggestions. The overall performance of the prototype helps extract information from the end-users/client for the design team to improve the design of the future building.

Results		
The Prototype	**Requirements/wishes**	**Suggestions/Improvements**
Level 1 - Design proposals for offices	Furniture placement	Light walls
	Room aspect	Storage space
	Doors/windows type	Corner sofa
	Common spaces	Vegetation area
	Room size	Unpractical stairs 3rd floor
Level 2 - Collaborate with other participants to design a classroom	Furniture placement	Pleasant aesthetic
	Furniture proposals	Individual desks
	Furniture size	More lights
	Combine ideas	Electricc socket for each desk
Level 3 - Lighting and weather influence	Enough light in the rooms	More electric lights
Level 4 - Free walkthrough	Easy navigation through the building	Lacks accesibility for persons with disabilities
		Missing railings
		Impractical spiral staircase
		Outside common areas
Level 5 - Follow the route	Common areas proposals	Toilets too small
	Room sizes	Toilet for persons with disabilities is unpractical
	Door sizes	Toilets nearer to the lunch area
Level 6 - Escape from the building with the help of arrows	Clear and safe escape route	Some railings might be dangerous in case more people try to escape at the same time
	Safety equipment noticable	
Level 7 - Alternative escape route	Clear and safe alternative escape routes in case of emergency	Signage missing
		Alternative escape routes should be considered

Table 12 - Results from the prototype testing

Level 1 Design proposals for study rooms A, B, C, D

Each of 6 participants rated four design solutions for study rooms from 1 to 4 (from the best to the worst) in Level 1. The table below shows the sums of the allocated points. The results indicate that proposals C and D are the most functional, according to the test participants. On the other hand, A and B were not viewed as the most suitable options and received varying feedback, positive and negative. For example, they were considered to be too small, or the choice of furniture was not ideal for everyone. Most participants preferred rectangular tables with chairs on both sides over a long, one-sided table or rounded solution.

Rating results	
1st Proposal C	**11**
1st Proposal D	**11**
3rd Proposal B	**16**
4th Proposal A	**22**

The most convenient furniture and interior design were considered relaxing light walls, modern desks, tables with matching chairs to accommodate an entire group, storage appliance (shelves, cupboards, corkboard to pin drawings). Other suggestions were bronze, grey, or dark furniture with a light interior and leather chairs.

Windows and doors received mostly positive feedback due to solid materials of doors and overall openings' appearance. For example, Participant 2 said regarding windows with a view to the hallway: *"Maybe door partition/window from the common hall to the room can have some curtains, so the group can draw them, in case they are working on a project with confidential data/information, so no one looks in from outside."* Participant 4 stated," *I really liked the black doors, they look modern, for some rooms perhaps bigger windows are needed."*

Additionally, for level 1, simulation made in Simlab Composer was incorporated. The participants were asked to test designing and annotation features while wearing HMD Oculus Quest. For example, they could choose furniture from the provided library and put them into virtual scenery. The goal was to design an office in the university following their wishes.

The prototype has been tested on the laptop, and for the VR experience, it was used an HMD Oculus Quest, together with a test building simulation created in Simlab Composer, for testing features of designing and annotation that we could not implement it in the prototype in the given timeframe. The participants' benefits and improvements are presented below, as well as how they designed an office room in the VR simulation (*See Figure 57*).

Benefits

- A better understanding of the design
- Easier navigation in the VR
- Easy understanding of the VR system
- Easy designing option

Improvements

- Teleportation gives sickness
- The gliches from the beginning
- More furniture options
- Better assets for Unity
- More advanced hardware

Figure 56 - Level 1 of the prototype tested in Simlab Composer

Usually, people experience locomotion sickness when they are in a virtual simulation using a head-mounted display. This happens typically due to lack of hardware to keep up with rendering the environment as quickly as possible, using VR standing/seating, active/passive, gender, age, illness, or duration of the VR exposure. However, 2/6 of the testing participants experienced the sickness in VR because of the teleportation feature in Simlab.

Other symptoms of VR sickness include apathy, discomfort, drowsiness, disorientation, eyestrain, fatigue and the factors creating this condition have been studied by researchers, which include: duration of VR exposure, age of the user, gender, illness, field of view, usage of VR standing/seating, active/passive

Level 2 Collaborate with other participants to design a classroom

Most of the end-users seemed to enjoy working together to choose the common design for a classroom. Their consensus referred to individual desks (e.g., Participant 1 said, "*My ideal would be individual desks that can be connected for group work.*"), linked electricity socket, easy to clean, and calming materials. Participants 4,5,6 chose one of the model's displayed options as a perfect single desk solution, alternatively instead of a grey surface – wooden texture.

Level 3 Lighting and weather

Throughout the level, the participants did not observe any building issues besides some concerns about more luminescent light needed in the bigger rooms during the night-time. For example, Participant 4 said, "*Maybe some rooms need more light, but overall everything goes well together. I like the feature of how light and weather are changing. I have not seen anything out of place while walking around*."

Level 4 Free walkthrough and Level 5 Follow the route

The participants enjoyed the experience at these two levels. It had given them an informative investigation of the building. They noted a few issues such as an impractical spiral staircase on the ground floor, too small toilets, a potential lack of accessibility for disabled people in the toilets, and in case of fire when the elevator is turned off. (For example, Participant 3 said, "*The toilets were really the minimum for regulations, I guess, they are very small, the one for disabled persons seemed fine, although, there must be some design mistakes regarding the sink placement*".) The sink's location was intentionally left to be higher than it should be to see if the participants would notice an error, and all of them have discovered the mistake.

Participants 1 and 4 were concerned about the kitchen on the 2^{nd} floor. They preferred it to be a closed solution in a separate room. Moreover, half of the end-users found printing rooms to be too small. Other comments included the need for plants to decorate the building's interior and bigger toilets with showers for occupants that spend an entire day at the university (Participant 5).

The end-users were conflicted about the big open hallway. They thought it was a nice spatial and modern solution, but at the same time, some of the space could be used for bigger/extra spaces – e.g., offices or classrooms.

Moreover, level 5 was timed how much it takes them to check the requested areas and follow the route. They completed it between 3:20 and 5:22 minutes before writing feedback.

Level 6 escape from the building with the help of arrows, Level 7 alternative escape route

These tasks were the most entertaining for the end-users, and they felt attached to the experience. Level 6 was easy for them to follow and complete. However, the last level caused some difficulties. Participant 5 said, "*Really difficult, I couldn't find the available staircase, but finally, I found the evacuation stairs."* Participant 2 expressed his opinion *"in a live-fire situation with multiple people rushing to the exit, people could get hurt if they get pushed over railings on the stairs leading to the ground*." […] *Very difficult to find the exit compared to Level 6 question*."

The participants completed the tasks relatively similar. Level 6 took them between 1:02 to 1:56 minutes to escape from the 3rd floor. In comparison, Level 7 from the same starting point results in the time frame of 1:52 to 2:08. Furthermore, the end-users were asked to note how many firefighting equipment they spotted on the way, 4 out 6 test people gave a correct number – three, while 2 test persons saw only 2.

Throughout the study, the end-users noticed various errors such as missing railings in a few staircases, one door opening in the wrong direction, a sink in the toilet for disabled people placed too high.

The answers to the general questions asked at the end of the testing show that the participants would prefer to test or at least walkthrough in virtual reality in the future building, rather than only looking at drawings or renderings. They also said they enjoyed the different tasks they had to perform in the simulation, such as escaping from the fire. Level 1 and 2 were also highlighted to provide the most input for the design investigation.

More detailed feedback was gathered from specific questions (e.g."*11.What do you think about the proposed locations of the common areas*[…]?" than direct types *(e.g., 10. Have you noticed anything unpractical while following the route? Describe your experience.), where the end-users answered with short comments.*

The participants understood the navigation principles almost instantly in both Desktop-view and in HMD VR despite most of them having little to none experience in using VR headset. However, a few test people had initial difficulties with mouse movements or teleportation in VR. 3rd person character was found to be easy to steer and a very enjoyable mechanism in the game.

In the end, they all agreed that a simulation like this one would have even more potential to be used if it would have been web-based.

These results will be discussed in the next chapter together with the future development of the prototype, and finally closing the report with the conclusion by answering the problem statement of this report.

Chapter 7. Discussion and Future development

This chapter presents the importance, relevance, and meaning of the report's results and includes suggestions for future prototype development. It explains key findings and shows how they relate to the literature review, interviews, and the research question. The purpose of testing the serious game was to validate the potential of the VR simulation for extracting requirements/wishes from end-users and, at the same time, to improve collaboration and communication between the design team and future occupants. In VR, 2 out of 6 participants experienced motion sickness, which can affect the user involvement process.

A simple walkthrough in Virtual Reality allows the end-users to express information that otherwise might be misunderstood by the design team. The study shows the importance of the correlation between the design team and the end-users/client in the design stage by involving them earlier in the process and understanding their requirements/wishes regarding accessibility and functionality of the future building's interior.

Thanks to interactive and immersive scenarios, the designers can guide a story in a simulation to collect end-users' input - knowledge and requirements. For example, pre-defined paths and viewpoints (level 5) are suitable tools to get participants to check certain building's facilities and judge design functionality and accessibility. Common areas, hallways, toilets, kitchens, and laboratories were instances used in this project simulation.

The level 5 results indicate that the test users completed the tasks quickly (up to 5:22 minutes per participant) while providing informative feedback about more appropriate sizes (*toilets are too small*), concerns about accessibility for disabled people, open kitchen plan, and the number of common facilities. It shows that the end-users might not be completely satisfied if the design team meets only the building regulations. Based on the input, the designers can optimize solutions early in the design process to fit with the group's general consensus.

In contrast, a free walkthrough task can give general feedback on areas that might need more considerations. For instance, while investigating the building without any restrictions, the end-users had conflicting views on the ample open space. Thus, designers can find an alternative solution to balance these perspectives.

Testing with the participants also showed that it could be used as a visual model checker. The intended error in the toilet for disabled people was detected by all of them. They were able to discover also the design imperfections left intentionally throughout the game's levels. It shows how people with different backgrounds can identify mistakes in a building. Even participants without technical knowledge provided valuable input (4/6 participants did not have architectural or construction background). Thus, the study indicates this serious game works as a step towards improving the collaboration and communication between the client/end-users and the design team.

Concerning the type of questions asked throughout the process, the study demonstrates that it is more efficient to request opinions on a specific theme (e.g., location of the common area) rather than asking to describe overall experience during a particular task. Moreover, the data suggest that the designing scenarios (1 & 2) provided the most information regarding the end-users' needs. The designers can narrow down different proposals for the study rooms to the ideal options. Similarly, the participants designed offices and the lecture halls from the available 3D objects set by the architects. Scenario 3 weather and day-night features demonstrated a possibility to extract end-users' input on lighting preferences in the building.

Furthermore, scenarios 6 and 7 for escaping in case of emergencies were the most enjoyable and compelling levels for the participants. They managed to get out of the building quickly (up to 1:56 minutes per participant with the help of arrows, and 2:08 minutes for the alternative path). Additionally, not everyone found all the firefighting equipment on the way. Such tasks can help designers to improve the overall design and signage if necessary.

Despite the fact that the participants have never or barely used VR in the past or recently, they managed to understand the technology and the serious game very quickly. Similarly, desktop view navigation was also not difficult to understand, especially with 3rd person character. Thus, a more developed game would not require a lot of training of the end-users/client before playing if the user interface is friendly and simple.

The communication and collaboration in the design phase must be enhanced further if the project's complexity gets higher. The data collection from the interviewees and the literature findings support that the design changes are frequent later in the construction phase. Integrating the end-users actively in the early design phase can reduce cost overruns and time delays.

Data extraction from this serious game plays an important role, even at a small scale, with questions and screenshots taken by the players. However, with automation coming into the discussion, the data from different groups of users (students, hospital personnel, etc.) can be exported and stored in a database for future use.

Future studies could address such a prototype to a larger number of participants during a longer timeframe to find a more complex data set and combine data tracking technologies to ease the understanding of end-users/client requirements. Additionally, the prototype could be tested in the architectural companies with the end-users of the specific projects.

Future development of this prototype can include different collaboration features for the design team and the end-users to clearly state requirements. Annotation features give the user the potential to express information directly in the simulation through recordings or sticky notes left in different areas and screenshots.

During the literature review, it was discovered that there is a shortage of methods for transferring the information from game engines to 3D modeling software. Therefore future development in this area can focus on automating the process of sending input back into the BIM model. For example, the game can be further developed to create a bi-directional data exchange environment between BIM software and VR simulation, where also the design team members can work together.

Further research is needed to determine the most optimal way to engage end-users in this type of simulation, Desktop-based, VR with a head-mounted display, phone-based, or Web-based interactive simulation.

Chapter 8. Conclusion

Game engines have a vast potential to encourage the development of VR and SG simulations to help the AEC industry and the facilities management with innovative solutions. Moreover, findings from the literature review support VR and game engines' use for various purposes, including emergency evacuations, design review, and learning experiences such as safety on site for workers.

During this research that covers literature review and information from professionals working in the industry, it became clear that end-users and client requirements or wishes are not explored to their full potential by the design team. It is due to traditional practices to include end-users in the design stage. Such methods lack accuracy resulting in design changes because of limited involvement of the end-users/client in the design stage.

The proposals are usually conducted in the form of paper drawings, conceptual maps, renderings, videos, and digital models. It sometimes leads to misunderstandings between clients and designing teams as the intended users may have problems with accurately expressing what they really mean. The end-users, when they are involved, are usually shown physical mock-ups built to represent real spaces. It is a time-consuming process that does not necessarily result in specific information about what the requirements are.

There are different types of future occupants, and each of them holds a unique perspective on practical solutions, expectations, and potential limitations, for example, regarding functionality and accessibility. They know a particular type of building and have an insight into requirements that might have been overlooked in the design process. Therefore, obtaining feedback, formulating wishes, and getting future occupants involved actively in project development are crucial to delivering high-quality products.

The end-users' active involvement can shorten the initial planning phase, and at the same time, it makes it possible for the architects to spend more time on the optimal solutions. VR interactive simulations create an opportunity for the designing team to let the end-users to test the proposed design. It leads to the main question of this research:

"How can BIM, Virtual Reality, and Serious Gaming be integrated to improve collaboration and communication between the design team and the end-users in the design stage of a public building?"

The project consists of a framework (found in 5.5. User Environment design) and workflow (found in 6.2. Development of the prototype) that presents processes and methods for developing an own immersive game without using many paid options on top of core BIM software. The vital component of providing an interactive simulation to extract end-users' knowledge is to prepare a detailed virtual world to sustain a realistic experience. Thus, the starting point to integrate VR and SG is to use a building information model after the architects are ready to test their design solution with the end-users.

For the framework's validation purposes, Autodesk Revit and Unity were used to develop the prototype. The BIM model can be imported to a game engine, for example, via 3Ds Max, where the model is optimized. Alternatively, it can be transferred using a free plug-in, Twinmotion.

Next, the VR simulation can be created by following the workflow's principles for developing SG's narrative based on a project type. After the game development, the participants were invited to play it and asked to provide feedback during and after the testing via audio, screenshots, videos, and the questionnaire. The outcomes consist of requirements/wishes from the end-users/client, such as room location, furniture placement, room design, common area proposals, and clear and safe escape routes.

The serious game's purpose was to validate the concepts presented in the report. The distinct scenarios acted as tools to extract the end-users' actual needs, provide design consistency, usability, functionality, and safety. The established objectives in sub-chapter 5.6. Paper prototyping guided the game's storyline.

The developed simulation can be incorporated to improve collaboration and communication between end-users and the design team based on the simulation testing outcomes. Moreover, throughout the research, the following sub-question was formed:

"How can an interactive VR simulation of a construction project help the design team to obtain requirements or wishes from the end-users and the client?"

An interactive VR simulation of a construction project can offer the end-users or the client a more straightforward and more understandable way to visualize and test a building for accessibility and functionality. Game engines make it possible to create an own simulation/game that consists of a VR built-in platform and Serious Gaming concepts. The designers can demonstrate proposals in an interactive way and apply a narrative to extract essential input from the building's future occupants.

Seven proposed levels of the prototype act as examples of how requirements and wishes can be investigated with the support of a game engine, VR, and SG. Getting this input has the potential to minimalize design changes in the later stages of any project, and at the same time, reduce costs and time to finish construction of a building. The suggested solution is a cost-effective method as most of the tools applied in the prototype are free to use on top of common BIM designing platforms.

The project's findings challenge the most common practices (e.g., 3D models, drawings, videos) of how the information is presented to clients, if and how end-users are involved in the designing process, and confirm the potential of the discussed technologies and concepts throughout the report. The immersive technologies, VR, and AR have proven to have the possibility of becoming an essential part of the AEC and FM industries. The extended reality tools enable users to investigate digital models as if they were next to the displayed objects (VR) or to experience added virtual entities on top of the real environment (AR).

The report's contributions consist of reviewing existing publications regarding technologies such as BIM, XR technologies, SG; analysis of popular VR software for AEC; data collection with interviews of professionals from the industry; design of the prototype (user-centered design – adapted contextual design); establishing framework and workflow; the prototype's development process and testing the created game with six participants.

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