DEVELOPING BUILDING INFORMATION MODELLING BASED VIRTUAL REALITY AND MIXED REALITY ENVIRONMENTS FOR ARCHITECTURAL DESIGN AND IMPROVING USER INTERACTIONS WITH SERIOUS GAMES

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ABSTRACT

DEVELOPING BUILDING INFORMATION MODELLING BASED VIRTUAL REALITY AND MIXED REALITY ENVIRONMENTS FOR ARCHITECTURAL DESIGN AND IMPROVING USER INTERACTIONS WITH SERIOUS GAMES

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Virtual Reality (VR) provides an interactive experience for its users in a fully artificial computer-simulated environment while Mixed Reality (MR) forms environments by mixing the real world and the virtual world elements together. In the first part of this thesis, an architectural visualization and design tool, which is based on Building Information Modeling (BIM), is developed for VR, MR and personal computer (PC) environments. BIM provides detailed information and tools to professionals so that they can develop and manage buildings and infrastructures efficiently. In the second part of this thesis, two tutorial-like serious games, based on VR and MR environments, are developed to improve the users' overall experience and to ease the user interactions in virtual environments. The developed tool and the serious games were tested by architects and game developers, and were evaluated from presence, usability, and technology acceptance perspectives. The results show that both the tool and the serious games were perceived positively in terms of beforementioned aspects and their usage in BIM-based models for VR and MR environments can enhance the design workflow in architectural design.

Keywords: virtual reality, mixed reality, building information modeling, architectural design, human-computer interaction

ÖZ

MİMARİ TASARIMLAR İÇİN YAPI BİLGİ MODELLEMESİ TABANLI SANAL GERÇEKLİK VE KARMA GERÇEKLİK ORTAMLARININ GELİŞTİRİLMESİ VE CİDDİ OYUNLAR İLE KULLANICI ETKİLEŞİMLERİNİN İYİLEŞTİRİLMESİ

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Sanal Gerçeklik (VR), kullanıcılarına tamamen yapay ve bilgisayarla simüle edilmiş bir ortamda etkileşim deneyimi sağlarken, Karma Gerçeklik (MR), gerçek dünya ile sanal dünya öğelerini bir araya getiren ortamlar oluşturmaktadır. Bu tezin ilk bölümünde, VR, MR ve kişisel bilgisayar (PC) ortamları için Bina Bilgi Modellemesi'ne (BIM) dayanan bir mimari görselleştirme ve tasarım aracı geliştirilmiştir. BIM, binaları ve altyapıları verimli bir şekilde geliştirebilmeleri ve yönetebilmeleri için profesyonellere ayrıntılı bilgi ve araçlar sunmaktadır. Tezin ikinci bölümünde ise, kullanıcıların genel deneyimini geliştirmek ve sanal ortamlardaki kullanıcı etkileşimlerini kolaylaştırmak için VR ve MR ortamlarına dayanan öğretici iki ciddi oyun geliştirilmiştir. Geliştirilen araç ve ciddi oyunlar, mimarlar ve oyun geliştiricileri tarafından test edilmiştir ve buradalık, kullanılabilirlik ve teknoloji kabulü perspektifleri açısından değerlendirilmiştir. Sonuçlar, hem aracın hem de ciddi oyunların yukarıda belirtilen yönleriyle olumlu olarak algılandığını ve VR ile MR ortamları için BIM tabanlı modellerde kullanılmalarının mimari tasarımdaki tasarım iş akışını geliştirebileceğini göstermektedir.

Anahtar Sözcükler: sanal gerçeklik, karma gerçeklik, yapı bilgi modellemesi, mimari tasarım, insan-bilgisayar etkileşimi

To My Family

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AEC	Architecture, Engineering and Construction
BIM	Building Information Modelling
BOOM	Binocular Omni-Orientation Monitor
CAD	Computer-Aided Design
CAVE	Cave Automatic Virtual Environment
CRT	Cathode-Ray Tube
HMD	Head-Mounted Display
HUD	Head-Up Display
ISO	International Standards Organization
MR	Mixed Reality
PC	Personal Computer
RV	Reality-Virtuality
SDK	Software Development Kit
SUS	System Usability Scale
TAM	Technology Acceptance Model
UI	User Interface
VR	Virtual Reality

CHAPTER 1

INTRODUCTION

Virtual environments (VE) drew lots of attention in the last decade with the big companies' investments such as Oculus' acquisition by Facebook [1], companies like Google and HTC's investments in the area [2], reduction of production costs of the virtual environment head-mounted displays (HMDs) [3] and rapid growth in the computer technologies in both hardware and software. This thesis focuses on the use of virtual reality (VR) and mixed reality (MR) environments in architectural design domain.

In the first part of this thesis, an architectural visualization and editing tool, which is named as HoloArch, is described in detail. HoloArch is developed for VR and MR environments to create a Building Information Modelling (BIM) based sustainable workflow between traditional two-dimensional (2D) design tools and virtual environment based three-dimensional (3D) visualization tools.

In the second part of this thesis, two tutorial-like serious games are presented to improve user interactions between virtual reality and mixed reality environments.

Both the developed tool and the games were tested by architects and game designers, and the outcomes were evaluated using the questionnaires of presence, usability and technology acceptance model (TAM).

1.1. Motivation

The research problems of this thesis and the motivation are the joint studies done in collaboration with METU Faculty of Architecture and they are the outcomes of two METU grants funded by Middle East Technical University (METU).

Main objectives of this thesis are listed as:

- Develop a functional VR- and MR- based architectural visualization and editing tool,

- Visualize a 2D complex analysis data in 3D for an easier comprehension for the users of the tool,

- Make a comparison between VR and MR environments from an architectural design perspective,

- Develop functional games to help and improve user interactions with VR and MR devices,

- Test the tool and the games with architects and game designers by evaluating their experiences by presence, usability and technology acceptance perspectives.

1.2. Developed Applications and Serious Games

For this thesis work, one architectural visualization and editing tool, HoloArch, and two serious games were designed and developed.

HoloArch is a BIM-based architectural design tool for VR and MR. HoloArch allows its users to visualize and edit their BIM-based architectural designs and models in VR and MR environments and transfer changes in the project back to the original design software and environment. This thesis work's initial motivation was creating a BIM-based visualization and editing tool for only MR environments. With this motivation, the tool was named as HoloArch—"Holo" part of the word comes from "hologram" and "Arch" part of the word comes from the word "architecture".

Serious games in thesis work aim to improve the players' and users' interactions with HoloArch and help them to learn how to interact with the tool and the virtual environment devices. With this motivation, two serious games, named as Shape Guardian and Architects and Buildings, were designed and developed.

First game, Shape Guardian is a fast-paced action-shooter game for VR and MR environments. In Shape Guardian's early game designs, players were shooting down basic 3D shapes such as spheres, cubes, and cylinders. With this motivation, the game was named as Shape Guardian. In the final design, basic 3D shapes were changed with flying drones and futuristic graphical user interface elements to have a sci-fi theme to create stronger immersion with an easier to understand game context. Second game, Architects and Buildings, is a slow-paced puzzle game for VR and MR environments. For the second game, puzzle genre was selected for its cognitive challenges presented to the player. Architects and Buildings game design was inspired from famous programming puzzle Tents and Trees[1]. For a more familiar game and architect-intriguing context, puzzle elements were changed with architects and buildings.

1.3. Contributions and Novelties

The main contributions of this thesis are as follows:

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[1] Tents and Trees Puzzles, Apps on Google Play, Available: https://play.google.com/store/apps/details?id=com.frozax.tentsandtrees&hl=en.

- A functional VR- and MR- based architectural visualization and editing tool, HoloArch, was designed and developed. With HoloArch, architectural design projects can be visualized in VR and MR environments, project elements' position, material data of doors, windows, shading devices can be changed, and the scale of door and window type objects can be modified. In HoloArch, architectural design software's 2D daylight analysis data can be visualized in 3D, and the project's BIM data can be made available in the virtual environment.

- Two VR- and MR- based serious games were designed and developed, which are Shape Guardian, and Architects and Buildings as mentioned in Section 1.2.

- Three events, one workshop and two user studies, were held to evaluate developed tools and games. In these events, tool's target audiences —architects and game designers— tested the HoloArch and the games. All the participants answered presence, usability, technology acceptance and other related questionnaires for evaluation purposes.

- Architectural visualization and design in MR environments are relatively new subjects and to the best of authors' knowledge, this thesis is the first comparative study that evaluates the performance of a BIM-based architectural design tool in both VR and MR environments.

The work reported in this thesis made the following joint publications possible:

- Ş. Akın, O. Ergün, E. Surer, İ. Gürsel Dino (2018). An Immersive Design Environment for Performance-Based Architectural Design: A BIM-based Approach. In Proceedings of the 4th EAI International Conference on Smart Objects and Technologies for Social Good (pp. 306-307). ACM.

- O. Ergün, Ş. Akın, İ. Gürsel Dino, E. Surer (2019). Architectural Design in Virtual Reality and Mixed Reality Environments: A Comparative Analysis. In IEEE VR 2019, the 26th IEEE Conference on Virtual Reality and 3D User Interfaces, Osaka, Japan.

- Ş. Akın, O. Ergün, İ. Gürsel Dino, E. Surer (2019). Improving Visual Design Perception by an Integrated Mixed Reality Environment for Performative Architecture. In Proceedings of the 7th eCAADe Regional International Symposium – VIRTUALLY REAL, Aalborg, Denmark.

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1.4. The Outline of the Thesis

The rest of the thesis is outlined as follows: In Chapter 2, background on the virtual environment, virtual environment research milestones, virtual environment-related definitions and serious games, are presented. In the following section, Chapter 3, the proposed tool HoloArch is examined in detail. In Chapter 4, two serious games, their purposes and rules are summarized. In Chapter 5, details of the organized workshop and user studies are presented and the results of these studies are given in Chapter 6. In Chapter 7, results are investigated in depth. In the last chapter, Chapter 8, thesis work is summarized and some possible future improvements are briefly introduced.

CHAPTER 2

BACKGROUND

In 1965, Ivan E. Sutherland introduced his vision on virtual environments in his well-known essay “The Ultimate Display” [4]. In this paper, the ultimate display is defined as “The ultimate display would, of course, be a room within which the computer can control the existence of matter”, a virtual world where it looks, sounds, tastes, smells and feels real. Sutherland’s vision is still yet to be achieved, but we have come a long way since his paper and with every new research, we are getting a step closer to achieve his vision.

2.1. Virtual Environment Research Milestones

The Telesphere Mask [5] and The Sensorama [6]: Morton Heilig, who is named as the “father of the virtual reality” by many, designed the first head-mounted device (HMD) “The Telesphere Mask” in 1960. This was the first step of his multisensory theater experience vision. With the Sensorama, he developed an apparatus for his multisensory theater experience dream where 3D images, stereo sound, wind and vibration through seats for a more immersive movie experience were used. The Sensorama was the first finished approach to create a virtual environment, but it was lacking in the feature of interactivity.

The Sword of Damocles [7]: Ivan Sutherland developed the first HMD in 1968 where the head tracking feature was properly applied. The Sword of Damocles showed its users’ computer-generated graphics on top of the real world.

GROPE [8]: GROPE project was started at the University of North Carolina (UNC) with United States Atomic Energy Commission’s funding’s in 1967 [8]. Their approach was dividing their main task into a four-step task which were; a two-dimensional (2D) version, a three-dimensional (3D) version tested with simpler tasks, a six-dimensional (three forces and three torques) version tested with simpler tasks and a complete scale version. In 1971, GROPE team at UNC finished their first prototype which made it the first force feedback system.

VIDEOPLACE [9]: VIDEOPLACE is an artificial reality art project developed by Myron Krueger in 1975, where interaction is the main concern. In this environment, two users enter into two different rooms where both of their body movements are captured and displayed on the screen in a 2D space, as silhouettes. Users can interact with each other’s silhouettes by moving in the room.

Virtual Environment Display System [10]: Virtual Environment Display System was a multi-input VR system designed by The National Aeronautics and Space Administration (NASA) which enabled efficient human-computer interaction methods for more complex interaction tasks.

VPL Research [11]: Jaron Lanier founded VPL Research in 1984 and was often regarded as the father of the virtual reality term. VPL Research has the first commercially successful and available virtual environment products such as The DataGlove, The AudioSphere and The EyePhone.

BOOM [12]: Fakespace Labs developed a commercial, mechanical virtual reality tracking device called Binocular Omni-Orientation Monitor (BOOM) in 1989. BOOM is a small box where users can look through its eye holes which contain two cathode-ray tube (CRT) monitors and can change the boxes' positions by using the device's mechanical tracking handles.

Walkthrough Project of UNC [13]: University of North Carolina's Walkthrough Project's mission is to build an interactive computer graphics system to allow its users to experience an architectural computer-aided design (CAD) model by simulating this model in a virtual environment [14].

CAVE [15]: CAVE, Cave Automatic Virtual Environment, is a room-sized, visualization project , developed in 1992. CAVE's approach on virtual reality is using stereoscopic image projection on room walls instead of HMDs to solve HMD's wider field of view and low-resolution problems in virtual environment projects.

Nintendo Virtual Boy [16]: In 1994, Nintendo announced its new device VR-32, which is known as Virtual Boy and it was marketed as the first console with a virtual reality display. Nintendo Virtual Boy displays 3D graphics in a tripod mounted display unit and allows its users to play games with a console gamepad.

Virtual environment researches of 2000s so far focused on creating and testing a wide range of virtual environment applications, making virtual environment devices cheaper and more accessible for commercial use [17]. Rise of mobile devices with high resolution displays, high computational power with 3D graphics capabilities and low production costs have created an opportunity for practical and accessible virtual environment devices. Advancement in other technologies and applications such as depth sensing cameras, motion controllers and better human computer interaction models created the current interest in virtual environments [18].

In 2019, there are more than 200 companies focusing and developing consumer products for virtual environments —Facebook, Microsoft, Google, Samsung, Sony, Apple, Amazon, and Valve are the biggest companies in the list. Gaming is the most popular use of virtual environment in the consumer part and many products and technological improvements are aiming at better immersion for players [19].

2.2. VR, AR and MR Relationship

Last decade of the 20th century was a really popular decade for virtual environment field, in both commercial and academic works. With this booming interest in this field, virtual reality (VR), augmented reality (AR), mixed reality (MR) definitions and their borders became vague. This situation created a need for better classifications for these word groups, i.e. a taxonomy study. In 1994, Milgram et al. introduced a reality-virtuality continuum in their paper as a way of classification approach [20]. They foresaw how hard it would be to describe the virtual reality and augmented reality and distinguish in between them. Instead of looking at the real environment and virtual environment concepts as each other's antithesis, they approached them as two polar sides of a continuum, hence the reality-virtuality (RV) continuum was born. RV continuum can be seen in Figure 1.

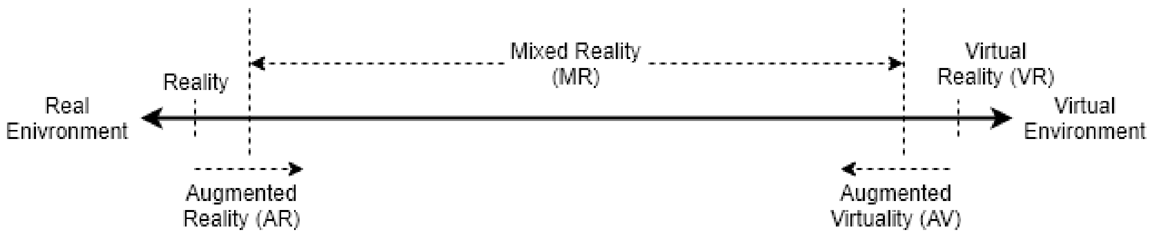

Figure 1: Graphical representation of Reality-Virtuality (RV) Continuum. Adapted from [20].

Tham et al. [21] defined modern RV continuum elements based on Milgram's work [20] as:

Virtual Reality: Computer generated artificial simulations, generally recreation of the real environment. Impersonating a person, as the dragonborn in The Elder Scrolls V: Skyrim VR [22] game, is a good example for virtual reality simulation and game.

Augmented Virtuality: Virtual environments that are controlled by real world data and a video chat through a phone camera are examples for augmented virtuality.

Mixed Reality: Blend of augmented virtuality and augmented reality. Any combination of real-world elements with virtual world elements.

Augmented Reality: Computer generated elements on top of an existing reality that combines virtual world elements with the real environment. Pokémon GO [23] is a good example for augmented reality applications. Azuma's definition for augmented reality is one of the most commonly used definitions. Ronald Azuma defined the augmented reality technology with three key features: 1) it should combine real and virtual content together, 2) it should be interactive in real-time, and 3) it should be defined in 3D [24]. These features also define the technical requirements of an augmented reality system.

Reality: Interactions that are limited by physical world laws such as space, time, material, and gravity.

Mixed Reality is still the most accepted definition to describe the technologies and tools that stand in the range between the real environment and virtual environments [25].

2.3. Virtual Environments and Architecture

The increasing interest in virtual environments created more advanced systems and application areas for different disciplines. For architecture, interest and implementation in virtual environment started with the design concept presentation [26]. Maze stated in his work that virtual environments that were used in architectural design till 2000s rarely focused on creation, development, form-finding and collaboration which keep architecture from benefitting virtual environments with their full potential [27]. Schnabel and Kvan stated in their work that immersive virtual environments offer new opportunities and solutions to architectural design problems which have not yet been used extensively in architectural design process [28].

Lots of early works in virtual environment and architecture indicate that as computational technology advances, more sophisticated design and interaction methods are needed and developed [29]. Hendrickson and Rehak [29] were not alone in their idea on virtual environments' and architecture's future, and in early 90s, this mind set shaped the last three decades' researches in virtual environment and architecture.

Freitas and Ruschel did a comprehensive research on virtual environment and architecture [30]. In their work, they reviewed 200 papers which were published in annual conferences between the years of 2000 and 2011. They cross-grouped and tagged published works in research areas (design method, architectural theory and history, performance evaluation, human interaction, representation, process and management), emphasis (education, application, collaboration, visualization, practice, and theory), and technology development stage (specification, development, application demonstration and evaluation). It was observed that, in research areas, top three areas were design method, architectural theory and history, and human interaction. In 200 publications, top three observed study emphases were visualization, application and theoretical discussion. Top three observed studies in technological development in virtual environments and architecture were technology evaluation, system or tool implementation and system or tool specification. In Figure 2, results of this work can be seen. The study by Freitas and Ruschel depicts that virtual environments are still not completely integrated into architectural practice and because of this missing connection, architectural practice cannot fully benefit from virtual environments.

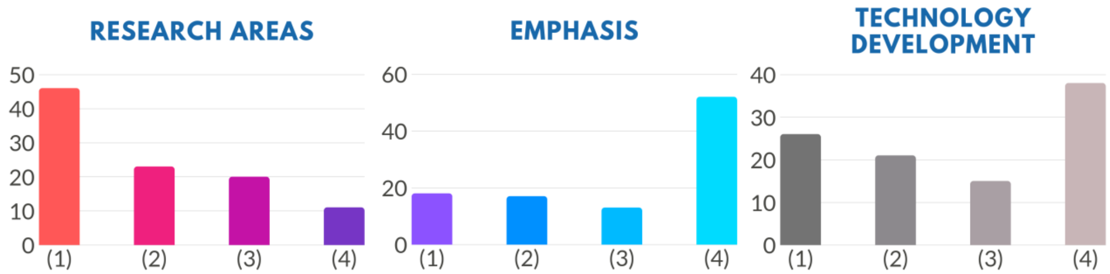

Figure 2: The distributions of virtual environment and architecture studies according to research areas, emphasis and technology development, as depicted in the study of Freitas and Ruschel [30]. Research areas: (1) design methods, (2) architectural theory and history, (3) human interaction, and (4) remaining groups. Emphasis: (1) visualization, (2) application, (3) theory, and (4) remaining groups. Technology Development: (1) evaluation, (2) implementation, (3) specification, and (4) remaining groups.

Virtual environments offer effective appliances for design and communication process in architecture by providing co-presence in both environments for users [31] and it has been found that design studios not taking advantage of full potential of virtual environments observed an absence of collaboration and communication between studio crew, which caused ineffective communication in the design context [32]. Yet, placing a designer in a virtual environment is not a solution to the abovementioned problems. Virtual environment technology in the architecture should be studied and explored in further detail. Hypothesis on what would work and what would not work should be challenged and tested. In virtual environment research, usability is a popular emphasis, but most of the researches are constrained within lab environment and they are not tested in the field. Architectural design makes a natural test bed for virtual environments, its applications and usability studies. This test bed should be used for case by case analyses in these areas [26]. Several sub-topics in virtual environments become more appealing for researchers in architectural disciplines for the last decade [30][33].

One of the research sub-topics aforementioned is immersive virtual environments and architectural design education. Abdullah et al. [34] focused augmented reality and its benefits in architectural education, in a specific case of students' comprehension of architectural construction. Alizadehsalehi et al. [35] provided a brief review and state of the art applications in virtual reality and its usage in Architecture, Engineering and Construction (AEC) education. Lin and Hsu [36] studied improving architectural design education in immersive VR environments by providing interactions to current visualization only tools. Gledson and Dawson [37] studied BIM-based immersive VR projects to improve learning process in architectural design education. Rodriguez et al. [38] used immersive VR environment as a supporting learning environment for conventional studios to improve learning process by enhancing students' engagement and motivation. Birt et al. [39] studied using immersive VR and AR environments together for understanding lighting analysis in architectural design education. Milovanovic et al. [40] provided a survey in virtual reality and augmented reality in architectural design education and proposed a system to support architectural education using virtual reality and augmented reality environments. In all these works, virtual environments improved the architectural education process from given perspectives, yet in most of the works, while virtual reality and augmented reality environments were tested, mixed reality environments were mostly left out.

Architectural visualization is another important topic in virtual environments and architecture research. Kim et al. [41] reviewed state of the art virtual environment applications and publications in AEC between 2005 to 2011 and made suggestions for future research directions. Architectural visualization had a big impact in both state-of-the-art applications and publications, and future trends. As smart phones gaining popularity, becoming cheaper and robust, researchers started to focus more on mobile-based solutions and research for existing problems. Woodward and Hakkarainen [42] focused on construction site visualization with their developed AR system, and its benefits on construction stage. Wang et al. [43] investigated AR's potential and future trends in AEC industry with a conceptual model. Fonseca et al. [44] studied benefits of AR visualization of building models against traditional printed plans and evaluated first year undergraduate architecture students' academic success. Fonseca et al. [45] investigated their hypothesis further [44] from the perspective of AR visualization's effects on architectural students' motivation. In both cases, architectural visualization in AR affects students in a positive way. Chi et al. [46] investigated trends and opportunities in implementation of AEC industry and AR solutions. Li et al. [47] studied virtual environment applications in construction safety with 90 published papers from 2000 to 2017, and they linked architectural visualization effectiveness with virtual environment construction safety tool's performance and success. Zaker and Coloma [48] studied virtual reality immersion's positive effects on collaboration and designed a review on a case. Dunston et al. [49] investigated VR visualization's benefits on clearer client understanding in planning and design phases on a specific case of hospital patient rooms' design review. Shiratuddin et al. [50] studied improving design reviews' effectiveness on immersive virtual environments by developing their own pipeline between design tool and visualization tool by using a game engine. Paes and Irizarry [51] investigated human factors and UI effects on immersive VR-platformed design reviews. Castronovo et al. [52] evaluated immersive virtual reality systems for design reviews, by their level of immersion for small and relatively bigger groups. Hamzeh et al. [53] focused on benefits of using mixed reality for design and construction phases in AEC projects. Visualization of the architectural projects for improved collaboration and design reviews is a trending sub-topic in this research area. An effective design review will minimize possible errors and conflicts, and by shortening the project life-cycle and reducing review times, it saves resources for the AEC industry personnel.

In these studies, it can be seen that AEC industry is currently using immersive virtual environments in an effective way. Most of the researchers mentioned in this subsection have a consensus on future possible benefits for integrating BIM and immersive virtual environments for the AEC industry.

2.4. Building Information Modelling (BIM)

Building information modelling (BIM) is defined by International Standards Organization (ISO) as follows [54]: "BIM unites the flow of construction processes with the specification of the information required by this flow, a form in which the information should be specified, and an appropriate way to map and describe the information processes within a construction life cycle."

BIM is one of the most rising trends in AEC) industry. In BIM, an accurate digital model of the project is virtually built. A completed BIM project contains the building's digital geometry data and the necessary data to support AEC industry's needs [55]. After the construction is completed, BIM can be used for maintenance and other post-construction operations.

BIM is a long-needed solution to AEC industry's problems which provides decreased project costs, increased productivity and quality, and reduced project delivery times [56]. Azhar et al. [57] listed the usage areas of BIM as follows: visualization, cost estimation, construction pipeline and facilities management.

BIM's main benefits according to Cooperative Research Centre for Construction Innovation [58] can be listed as: correct and detailed digital representation of a building, improved design, increased production quality, automated manufacturing and assembly processes and more effective and faster processes.

Like every other system, BIM also has a learning curve for its users. Lessening this learning curve is an important challenge to optimize BIM performance. In an AEC project, not only architects and engineers use BIM but also tenants, service agents and maintenance personnel, which makes lessening the learning curve more challenging and important [55-57].

Daylight analysis can improve building design a lot, but research shows that some architects and designers, who did not implement BIM-based design, have difficulties while using those tools since they are not compatible with their projects' design methods, or they find the analysis tools too complex [59-60]. One of the benefits of the BIM is its offering of a simplified daylight analysis process and integrated workflow between their design and analysis tool for its users. BIM provides its users with a high precision building performance data by simulation of the actual measured data instead of simplified design estimations [61]. Daylight analysis data are primary information when it comes to designing energy-efficient, high-performance structures since analysis data help its users to understand the effects of their design in energy [62]. Energy-efficient designs' main objectives are reducing the artificial energy need for heating, cooling and lighting, and better energy performance of the buildings starts in the early phases of the project design [63]. The advantages of integrating BIM based daylight analysis to design process over traditional methods can be summarized in three items [61]; performance results which were based on actual measured data instead of simplified design assumptions, BIM's detailed data to simulate and estimate system behavior, and producing evaluation and solution with multiple design alternatives.

Autodesk Revit provides different BIM-based daylight analysis tools for high performance building design for different goals and metrics [64]. These daylight analysis tools are; Ecotect, Radiance, DAYSIM and 3DS MAX Design. There are also other BIM-based tools from independent developers that offer fully integrated daylight analysis plug-ins for Autodesk Revit, such as ElumTools [65] and DIALux [66]. Tools like ElumTools and DIALux offer its users a 3D visualization and walkthrough around the project in PC environment but not allow its users to interact with the project while visualizing. A number of previous works studied daylight analysis tools with the BIM model from different perspectives. Özener et al. [67] focused on integrating BIM-based daylight analysis to performative design process from educational perspective. Ecotect, Radiance and DAYSIM were used in their studies. Kota et al. [68] researched on daylight analysis and its integration to BIM environments using Autodesk Revit as a BIM tool and Radiance and DAYSIM as daylight analysis tools. Instead of having daylight analysis at late stages of the projects or at the end of projects as in the traditional methods, benefits of integrating BIM and daylight analysis into early design phases are currently attracting researchers' attention. Najjar et al. [69] studied BIM and life-cycle assessment (LCA) integration benefits in early design stages to improve daylight efficiency from design perfectives. Soust-Verdaguer et al. [70] studied the same concept aiming to reduce consumption. Röck et al. [71] proposed a new BIM and LCA integration in early project stages via visual scripting to reduce environmental impacts of the buildings. Environmental effects of the buildings are one of the long-term problems of the AEC industry and BIM based solutions are preferred to overcome those effects. Najjar et al. [72] studied BIM-LCA integration from an environmental perspective.

The reviews of Zhao [73] and Li's [74] show the state-of-the-art and trending topics, and BIM visualization in immersive environments and development of the visualization tools for the BIM in immersive environments were among the popular concepts. Most of the researches focused just on the visualization aspect of the immersive environments and not fully experimented the interaction options in immersive environments, even though interaction is an important feature of the immersive environments [75].

The visualization of daylight analysis simulation results in immersive virtual environments is a new topic. Natephra et al. [76] developed and proposed a VR visualization and editing tool for Autodesk Revit projects and they focused on BIM-based lighting visualization in VR environment for lighting performance analysis data. In Natephra et al.'s study, 2D visualization for lighting analysis data was performed. In another case, Alcini et al. [77] designed an underground city, Underground City of Montreal, and studied daylighting conditions in VR and its benefits for extremely large projects' simulation. Alcini et al. also focused on only VR environments and they used 2D visualization for lighting analysis data. Araujo [78] focused on light design and interactive immersive VR environments to ease the learning curve for the perform stage and lighting design tasks. In this work, it can be seen that using interactive immersive

VR environment can improve design process. Bahar et al. [79] focused visualization of 3D visualization of a 2D building's thermal performance simulation data in immersive VR environments. Araujo [78] and Bahar et al. [79] did not work with lighting analyses but focused on benefits of visualization of different types of analysis data in immersive VR environments.

2.5. Serious Games

Serious game, by its vaguest form, can be defined as a game, whose primary purpose is not entertainment, but training and education purposes in especially health, education and defense-related domains [80]. Idea behind the term can be traced back to Renaissance era philosophers, where they used the term "serio ludere" which can be roughly translated as "serious play (theatre)". Serio Ludere is basically using humor in plays to deal with serious matters [81]. First time "Serious Game" was used as closed to its current meaning in Clark Abt's Serious Games [82] book. In his book, Abt described serious games as: "Games may be played seriously or casually. We are concerned with serious games in the sense that these games have an explicit and carefully thought-out educational purpose and are not intended to be played primarily for amusement. This does not mean that serious games are not, or should not be, entertaining" [82]. Abt used his serious games approach to solve real life educational, governmental and industrial problems [83]. Michael et al. [80] define serious games as "games that do not have entertainment, enjoyment, or fun as their primary purpose". This generic yet comprehensive definition is one of the most accepted definitions today [83].

Although attention to serious games started to increase since early 2000s [81], they are almost as old as computer technologies. Early serious games were mostly named simulations and their aims were to simulate military and business scenarios, i.e. a training and test area for military officers and company executives to recreate dangerous to live scenarios [80]. The Oregon Trail probably was one of the most known serious games. The Oregon Trail, developed by Don Rawitsch, Bill Heinemann and Paul Dillenberg in 1971, was an educational serious game [84]. The Oregon Trail aimed to teach students 19th century pilgrim life and the Oregon Trail itself.

Djaouti et al. [81] referenced 2218 serious games developed and published till 2010 and examined them by their relevance to serious games definition by Michael et al. [80], and by their publication date and market size of different topics. From his works, it can be seen that attention to the serious game research exponentially increased starting from 2002. This increase in attention brought different and diverted approaches to the serious game research. The most popular subtopics are physiological, social, educational/informational and spatial effects on players [85].

Numerous studies show that playing video games can develop and improve cognitive, spatial and motor skills [86–98]. Connolly et al. [99] analyzed 129 published studies about the positive impacts of gaming and serious games, and showed that 22 percent of the works' (28 in total of 129 works) outcomes depicted that games had positive effects on perceptual, cognitive and motor skills. Boyle et al. [100] updated Connoly et al.'s [99] work by using their framework and approach to the published works. Boyle et al. analyzed 143 studies on positive impacts of the games published between 2009 to 2014. Their work showed that 22 percent of the all works' (31 in total of 143 works) outcomes were games positive effects on perceptual, cognitive and motor skills.

In spatial tasks, for both basic and complex tasks, functional improvements were observed in various studies [89-94]. Some studies showed that these improvements could affect the players in the long term [93-98]. Most of the works in video games and their positive spatial skill improvements focused on action [89;92-93] and puzzle [91-93;99] genres. Spence et al. [93] compared various game genres by need of sensory, perceptual and cognitive function skills. They scored game genres on a 5-point Likert scale (5 being the highest and 1 being the lowest) for exercising level for different functions. Action game genre got 5 points on sensory and spatial skills, and 2 points on analytical and long-term memory skills while puzzle game genre got 2 points on sensory, 3 points on spatial, 4 points on analytical and 3 points on long term memory skills. Even though puzzle game genre couldn't get 5 points on analytical and long-term memory skills, it got the highest score in these sections. This work provided a detailed overview that action and puzzle games were complimentary for the aforementioned skills. In this thesis work, action and puzzle genres were selected as the genre of the tutorial-based games to benefit from these advantages.

Game technologies were used in various different disciplines with motivations such as simulation and training, and multidisciplinary studies between serious games and architecture is not new to the literature. Serious games to enhance architectural visualization was one of the most important subtopics in those multidisciplinary studies. Yan et al. [101] investigated BIM integration and gaming's benefits for real time architectural visualization. Researchers' motivation was using video games' ability to capture players attention to improve architectural visualization. Shiratuddin et al. [102] studied architectural design and visualization, and games assisted the students in a class environment. Boeykens [103] approached serious games from BIM and historical landmarks' architectural reconstruction aspects.

Serious games to improve AEC industries educational need is one of the most popular sub-topics in this area. Dinis et al. [104] studied different virtual environment (VR and AR in their case) game-based applications that were useful in civil engineering education and in the learning process. Ayer et al. [105] investigated AR-based serious games' positive effects in design education by developing an AR-based serious game and compared it against traditional methods. Valls et al. [106] studied serious games applicability in architectural education by testing against traditional methods for different fields in the architecture. Merschbrock et al. [107] studied BIM and serious game integration methods for improving AEC professionals' learning curve on the spatial layout of new projects. Wu and Kaushik [108] used BIM and serious games integration to design senior-friendly housing. In several studies [99-108], one of the purposes for game usage was to ease learning in newly introduced environments.

2.6. Evaluating the Performance Outcomes of Serious Games and VR and MR Environments

Evaluating developed tools, games and benefited environments is necessary to check if the tools and the games realized their objectives. There are numerous studies that focused on evaluation methodologies [109–115]. Calderon and Ruiz [109] reviewed the evaluation techniques that were used in serious games publications and their study shows that in 90 percent of the papers (92 out of 102 papers) questionnaires were the main evaluation method. The widely used questionnaires, which were also the main evaluation tools of this thesis, are explained in the following subsection.

2.6.1. Presence and Immersive Tendency Questionnaires

Presence can be defined as a person's experience of being in a place while he/she is in another place. Interdisciplinary usage of presence caused derived definitions from the beforementioned definition. Essence of presence [116] definitions is the state of being in displacement to another place. These definitions were redefined for virtual environments as; a person's experience of being in a virtual, computer generated world while he/she is in the real world. Garret [117] summarized the importance of presence in virtual environments in his work mentioning that presence increases the quality of the user experience. To evaluate presence in our VR- and MR- based tool and games, we used Witmer's and Singer's work [118] on presence questionnaire for virtual environments. They stated that two psychological states play an important role for experiencing presence; involvement and immersion. They explained the relationship of involvement and immersion states with presence as the user's degree of focus on virtual environment devices and this determines the user's involvement degree to the virtual environment experience, i.e. when the involvement is higher, the degree of immersion and presence increases.

2.6.2. Technology Acceptance Model Questionnaire

From early 1980s, information system research focused on developing, testing and implementing models that predict system use. In 1986, Technology Acceptance Model (TAM) was introduced by Fred Davis [119] in his doctoral dissertation and TAM became a widely accepted model for studying user's acceptance of technology since then. TAM focuses on two aspects —perceived usefulness and perceived ease of use— a relation between potential system usage and system characteristics. TAM was built on psychology-based research; mainly the theory of planned behavior and theory of reasonable action [119]. Over the years, TAM was finalized by Vanketash and Davis [120], and two improved versions TAM 2 by Vanketash and Davis [121] and TAM 3 by Vanketash and Bala [122] were developed and published.

2.6.3. System Usability Scale Questionnaire

One of the most important issues in virtual environment research is evaluating usability. There is a variety of of methods for virtual environment systems' usability and every one of them has different advantages and disadvantages over others. Some methods focus on user interfaces while others use heuristic evaluation methods [123-124].

In this thesis work, to measure systems usability, Brooke's [125] proposed questionnaire method, System Usability Scale (SUS) was used. Since 1986, SUS has been used to evaluate usability on websites, smartphones, applications, virtual environment devices and many more, and has become an industry standard with more than 600 referenced publications [126]. Bangor et al. [127] reviewed 2324 SUS surveys from 206 usability tests over a ten-year period and their study showed that SUS was highly reliable for a wide range of applications.

CHAPTER 3

BUILDING INFORMATION MODELLING BASED VIRTUAL REALITY AND MIXED REALITY TOOL: HOLOARCH

In this chapter, developed VR and MR based architectural visualization and editing tool, which is named as HoloArch, is presented in detail.

HoloArch is a VR and MR based architectural visualization and editing tool. Autodesk Revit is a BIM software designed for professionals in architecture and construction. Users design their buildings and its components in three-dimensional (3D) space and can access building model's database. With Revit's BIM information, users can plan and track various stages in their projects, from beginning to final construction and later maintenance [128].

HoloArch allows its users to visualize their Autodesk Revit projects in VR and MR environments, visualize daylight analysis data in a more user-friendly 3D graph, edit pre-selected features of their project and return those changes to Autodesk Revit when needed.

Daylight analysis in Autodesk Revit helps its users to perceive and evaluate how sunlight affects their project with project's current settings. Users can use this information to create more comfortable spaces, update lighting and cooling parameters. Daylight analysis in BIM generally tries to answer four fundamental questions, which are: 1) how to get more natural light, 2) does project get appropriate amount of natural light for its tasks, 3) is light well placed and 4) can use of artificial lights reduced with daylight [129].

3.1. Programming Language and Development Environment of HoloArch

Unity real-time game creation platform [130] and C# programming language are chosen in order to develop HoloArch. Unity is a real-time creation platform developed by Unity Technologies. As of version 2019.1.4 (released in 24 May 2019) platform supports more than 25 platforms across desktop, mobile, console, web, VR, MR and more. Over 66 percent of VR, AR and MR experiences on the market are developed in Unity, from game studios to movie directors [131]. Since Unity has a multi-platform support and HoloLens's main application platform is Unity, Unity platform us selected as the development tool. Unity's Editor Screen for HoloArch can be seen in Figure 3.

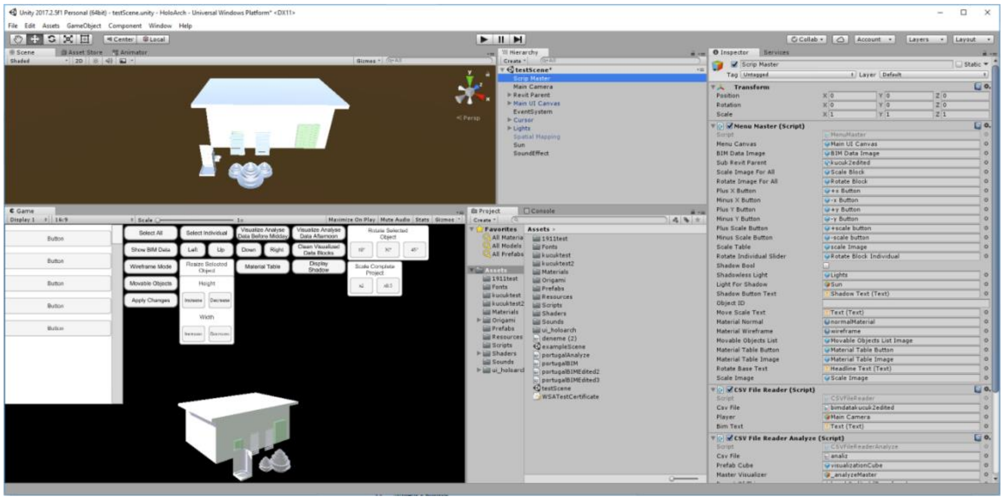

Figure 3: Developer screen of the HoloArch tool.

Besides Unity, OpenVR [132] software development kit (SDK) for the VR part of the application and Windows 10 SDK [133] for the MR part of the application are used.

C# is a programming language that is designed for Common Language Infrastructure by Microsoft. It is a general-purpose, multi-paradigm and object-oriented language that allows developers to build applications that run on .NET Framework [134]. Unity currently supports only C# programming language to develop applications and games.

3.2. System Workflow

HoloArch works together with Autodesk Revit program and provides a complete data input and output-related file reading and writing workflow. In Figure 4, HoloArch's workflow is shown in a diagram.

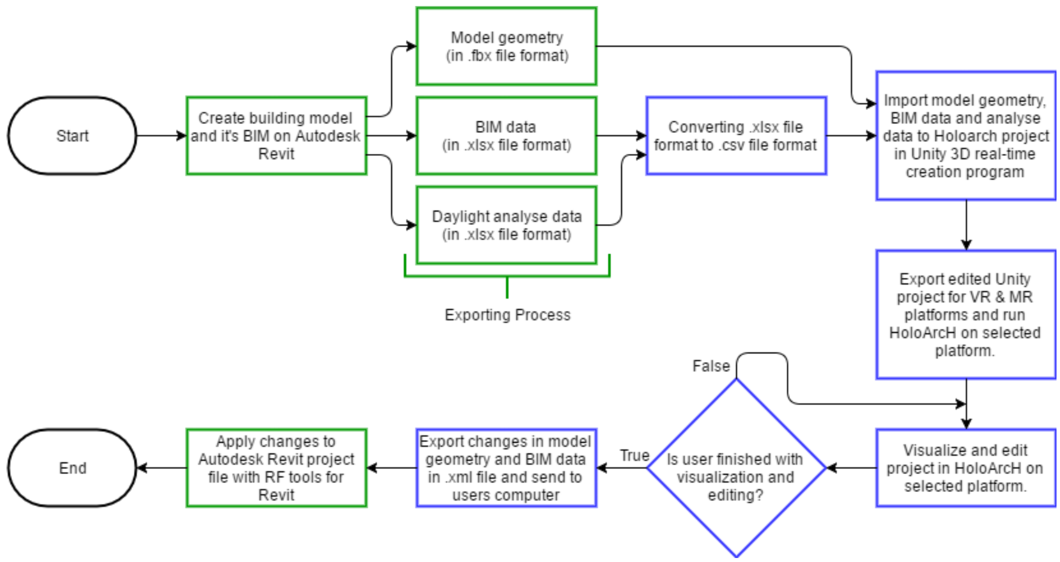

Figure 4: HoloArch workflow diagram (green diagram elements indicate the user's interaction with Autodesk Revit while blue diagram elements indicate the user's interaction with HoloArch).

HoloArch not only visualizes 3D model of the Autodesk Revit project in the selected virtual platform, but also visualizes each element's data by its unique identification (ID) from BIM data. For this purpose, exported project should contain BIM data and geometry data of the project while its objects act as individual elements and contain their unique ID.

Autodesk Revit enables users to export different file formats from its inbuilt features. These file types can support to carry the work on different platforms for uninterrupted workflow. However, when it comes to Unity, the file formats that Revit is capable of exporting are not completely compatible with the Unity yet. To overcome this workflow obstacle, a new exporting process is developed in this thesis and it is displayed in Figure 5. This exporting process can be examined in three stages:

- Model Geometry,
- BIM Data,
- Daylight Analysis Data.

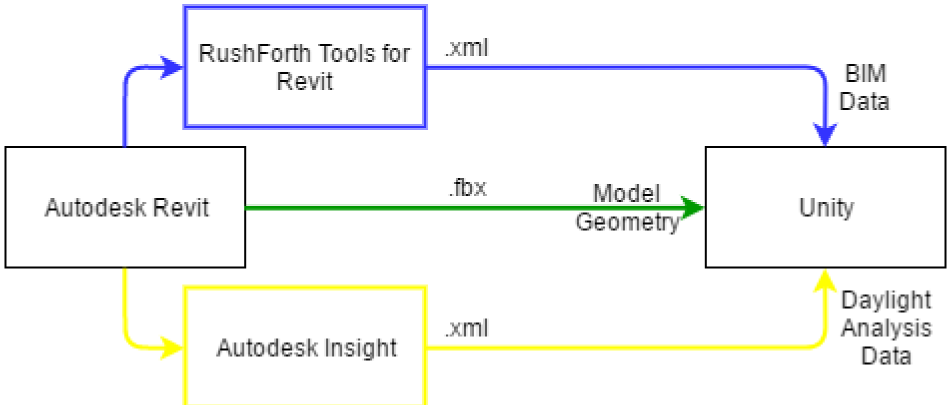

Figure 5: Exporting process of the HoloArch. Three stages are shown in different colors; green branch shows Model Geometry stage, blue branch shows BIM Data stage and yellow branch shows Daylight Analysis Data stage of exporting process.

3.2.1. Model Geometry Stage

Autodesk Revit currently supports following file formats as export option; CAD formats (ACIS SAT, DGN, DXF, DWG), DWF/DWFx, Building Site (ADSK), FBX, NWC, gbXML, IFC, ODBC Database (Microsoft Access, Microsoft Excel, Microsoft SQL Server), Images and Animations (Walkthrough – AVI, Solar Study – AVI, Images (JPEG, TIFF, BMP, TARGA, PNG)) and Reports (Delimited text (.txt)) [135]. However, its export capability can be expanded with additional plugins which provide outputs such as OBJ and DAE file formats that Revit does not support to export by itself. Unity currently supports following model file formats; FBX, DAE, 3DS, DXF and OBJ [136].

After various tests for Revit exported file format compatibility with Unity, FBX is selected as the model geometry import file format for HoloArch tool. With FBX file format, elements of the model (such as windows, walls, doors, etc.) imported as separate game objects with their unique Autodesk Revit IDs. Game objects with their unique Autodesk Revit ID in Unity editor window can be seen in Figure 6.

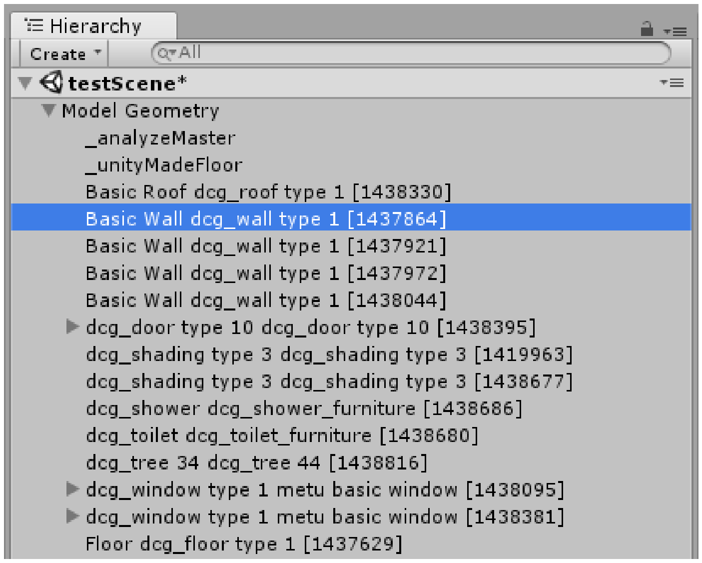

Figure 6: Game objects with their unique Autodesk Revit IDs, shown in Unity's editor window.

FBX files can be exported directly from Autodesk Revit with its settings or export settings can be modified with plugins. Various popular FBX exporter plugins such as Archilizer, TwinMotion's Dynamix Link and SimLab are tested and the results show that Autodesk Revit's own export method suits best for HoloArch. The comparison of FBX exporter methods can be seen in Appendix A.

3.2.2. BIM Data Stage

Building Information Modeling (BIM) is defined by The National Building Information Model Standard Project Committee as: "BIM is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition" [137]. One of the most significant features of BIM is its ability to store huge amounts of data about the building and its elements.

While transferring the model to Unity environment from Autodesk Revit, model geometry does not contain complete BIM data of the project. To overcome this problem, a commercial plugin for Autodesk Revit, which is called RushForth Tools, is used to extract BIM data in .xlsx file format. RushForth Tools can extract BIM data of the project with desired parameters such as element's unique ID. Currently, 35 different properties of each element are exported in HoloArch tool. In Table 1, exported element properties and the properties that can be edited in HoloArch tool can be seen.

Table 1: Table of exported element properties and properties that can be edited in HoloArch.

Exported Autodesk Revit Element Properties	HoloArch Tool
Length, Depth, Width, Height, Material, Frame Material, Glass Material, Tree Transmittance, Shared Coordinates X-Y-Z, Angle to True North.	Editable
Element ID, Category, Family, Type, Area, Volume, Thickness, Still Height, Offset, Rotation. Degrees, Structural Material, Comments, Analytic Construction, Solar Heat Gain Coefficient, Heat Transfer Coefficient, Visual Light Transmittance, Thermal Resistance, Thermal Mass, Absorptance, Roughness, Blade Angle, Blade Number, Blade Distance.	Not editable

A script is developed to parse BIM data into HoloArch tool by elements' unique ID's and match game objects with that parsed data element's unique ID. Building elements' BIM data, displayed in HoloArch, can be seen in Figure 7.

Figure 7: BIM data visualization in HoloArch. Visualization is displayed using HoloLens emulator.

3.2.3. Daylight Analysis Data Stage

Autodesk Revit's plugin Insight Lighting Analysis [138] simulates daylight and lighting analysis results and visualizes analysis data in 2D over model geometry. An Autodesk Revit screenshot can be seen in Figure 8.

Figure 8: Insight Lighting Analysis results are displayed in Autodesk Revit [138].

Insight Lighting Analysis plugin also automates scheduling for users to document light levels in their project. Insight currently provides 6 types of analysis, which are illuminance, daylight autonomy, LEED 2009 IEQc8 opt1, LEED v4 EQc7 opt1, LEED v4 EQc7 opt2 and Solar Access [139].

In this thesis, a new way of visualizing daylight analysis, in which huge amounts of data are displayed in a more immersive and natural way, is targeted. For this purpose, a 3D interpretation of 2D analysis data is created and this interpretation can be seen in Figure 9.

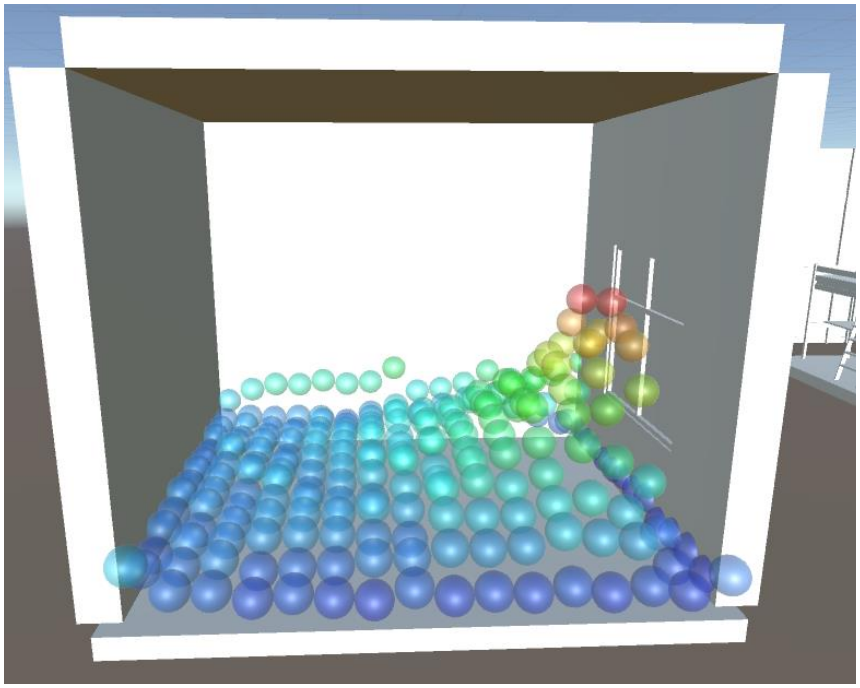

Figure 9: 3D interpretation of 2D daylight analysis in HoloArch.

In order to visualize daylight analysis data in HoloArch, Lux values and its coordinates in 3D space need to be provided by Autodesk Revit. Autodesk Insight exports these analyses in an .xml file format.

HoloArch tool parses daylight analysis data via a script using Lux values and its coordinates. Since Autodesk Revit and Unity use different types of coordinate systems (Autodesk Revit uses right-handed coordinate system while Unity uses left-handed coordinate system), coordinates are adjusted before data visualization. After the process of parsing, the same script instantiates spherical game objects and changes their color and position.

3.3. HoloArch Tool's Features

HoloArch tool has 9 different functions that its users can use in order to visualize and edit their Autodesk Revit project on HoloArch. In this subchapter, these functions and relevant user interaction methods are presented.

3.3.1. User Interaction Methods

To sustain Unity in user interaction between VR and MR environments, the designed user interactions are limited with gaze and interact. In both devices, gaze is one of the pre-defined ways of interaction and experiencing the virtual environment. Gaze is working as an equivalent of the mouse movement in personal computers (PC). User's head movement is tracked by the headset and with SDK libraries of the device, this rotation movement is used to calculate user's head orientation and where he/she is looking. HoloArch Tool draws a 3D cursor mesh on user's gaze point and a screenshot from the proposed tool can be seen in Figure 10.

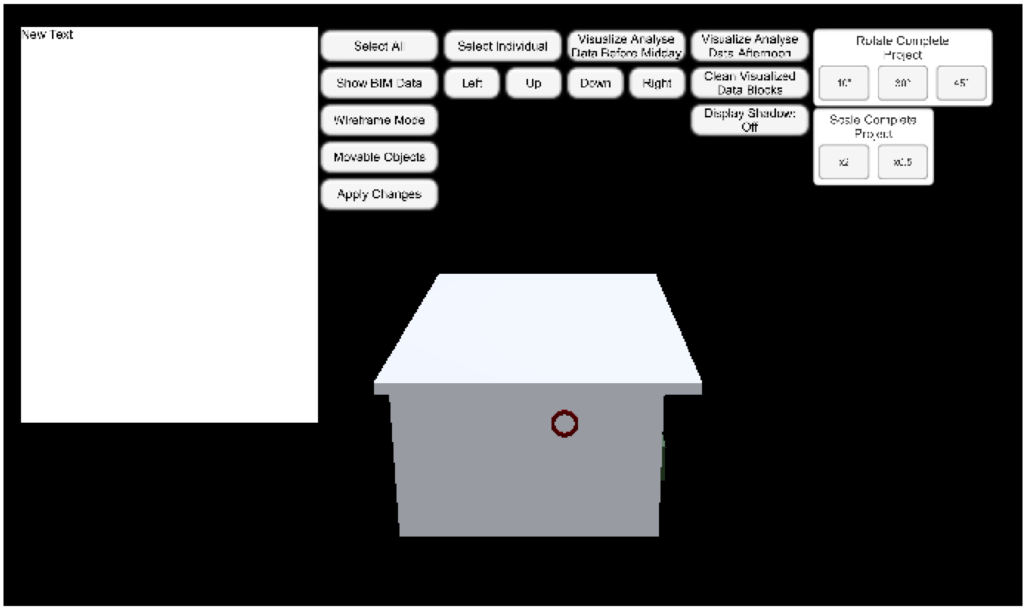

Figure 10: HoloArch cursor—the red torus shaped mesh on the wall.

When users are gazing down on an interactable object, HoloArch draws a cursor mesh on that object and they can interact with the gazed object via the air tap gesture (in HoloLens) or via triggering the pull on the controller (in HTC Vive).

3.3.2. Select All and Select Individual Buttons

Instead of creating different methods for individual game objects and for the complete Autodesk Revit project, a collider is added to every game object of the imported project. With this solution, when users want to interact with individual game objects, they initiate their action with clicking "Select Individual" button and when users want to interact with a complete project, they initiate their action with clicking "Select All" button. In Figure 11, HoloArch's user interface (UI) options can be seen for Select All and Select Individual functions.

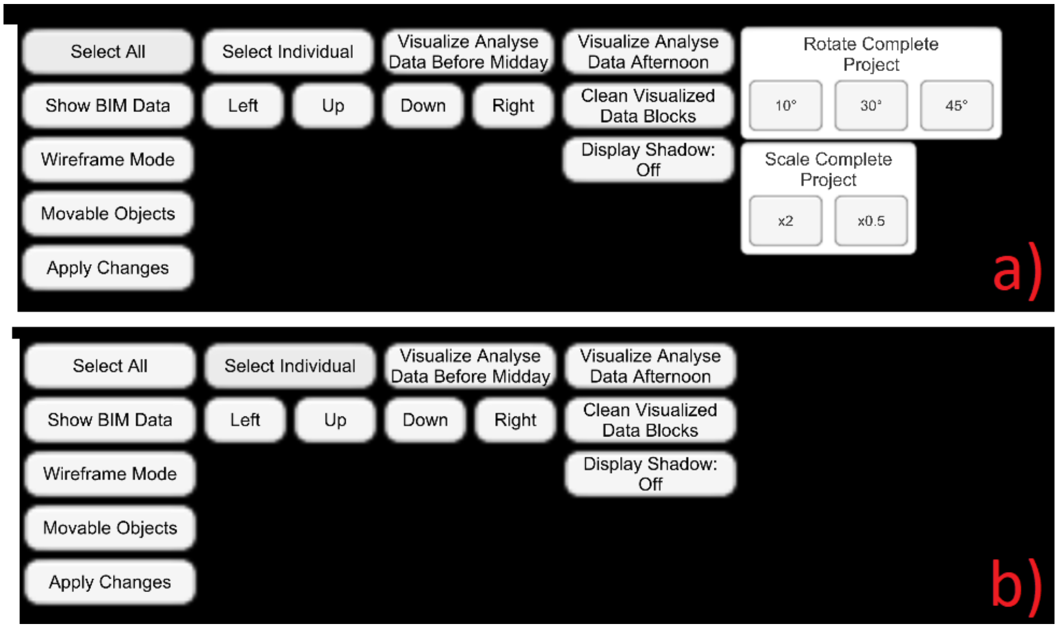

Figure 11: HoloArch UI after a) Select All button is pressed, b) Select Individual button is pressed.

3.3.3. UI Position Adjuster (Up – Down – Left – Right Buttons)

Gaze is the main interaction method in HoloArch and thus, traditional Head-Up Display (HUD) camera is not applicable for the interactable UI. For this purpose, a different approach for HoloArch UI is tried: when the application loads, UI appears in the 3D space by being projected on the mesh where the user is looking. In z-axis, UI is kept 1m distance from the user. For x and y axes, user adjusts UI's position with UI Position Adjusters button, Up and Down (in y-axis) and Left and Right (in x-axis). The locations of the buttons in HoloArch UI can be seen in Figure 12.

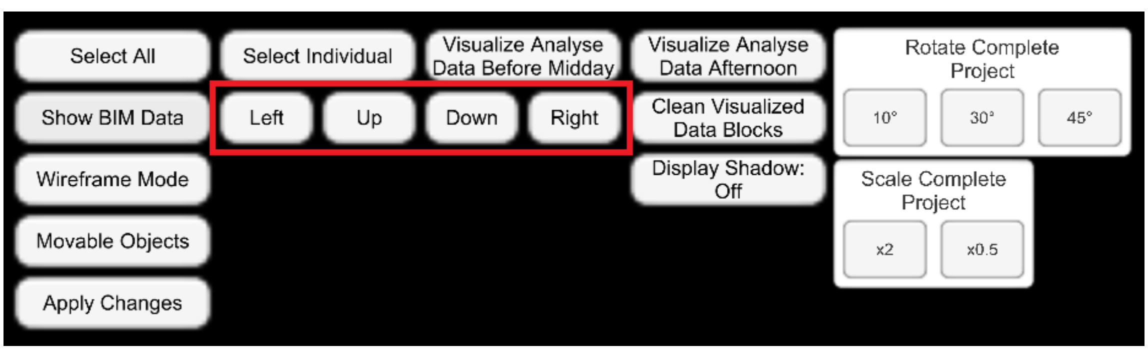

Figure 12: UI Position Adjuster buttons (shown inside the red rectangle) in HoloArch UI.

3.3.4. Apply Changes, Project Rotation and Scale Buttons

After user finishes with editing in HoloArch, he/she can save changes on the project and continue working on Autodesk Revit. "Apply Changes" button creates an .xml file in a designated file address in RushForth tools with the BIM data layout. Users can use this .xml file to apply the changes made on HoloArch to their Autodesk Revit project. Users can also change the project's rotation and scale by using the designated button.

3.3.5. BIM Data Display

In HoloArch tool, every individual game object has a unique ID with its BIM data. When a user gazes down on an object and interacts with it by air tap/trigger pull action, game object's BIM data are displayed on the left side of the UI with details—as can be seen in Figure 13. "Show BIM Data" button works as a toggle switch for enabling and disabling BIM data display image on HoloArch UI.

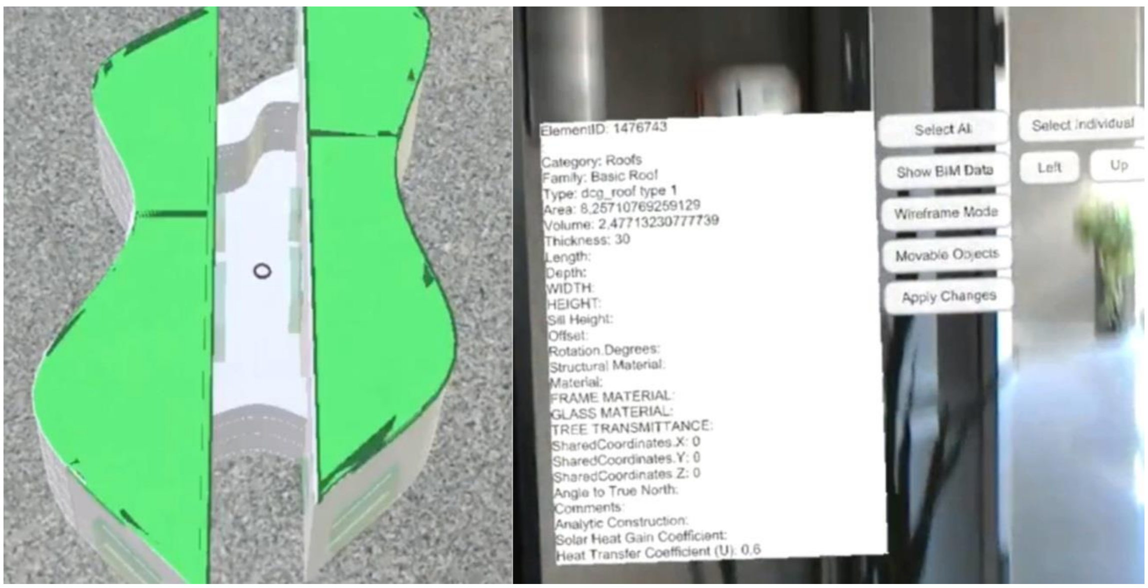

Figure 13: Displayed BIM data of a game object. On the left, selected project element can be seen as highlighted and, on the right, that game object's BIM data can be seen.

3.3.6. Visualize Daylight Analysis Data

Users can visualize Autodesk Revit Insights daylight analysis data in HoloArch with two buttons: "Visualize Daylight Analyse Data Before Midday" button for 9:00 am visualization data and "Visualize Daylight Analyse Data Afternoon" button for 3:00 pm visualization data. Currently, only these two selected hours data are imported. To clear HoloArch's project space from daylight analysis tool's data spheres, users need to press "Clean Visualized Data Blocks" button.

3.3.7. Wireframe Mode

When the wireframe mode is activated, it changes game object's material to a new material with a wireframe shader to enable the see-through function. "Wireframe Mode" button works as a toggle switch for enabling and disabling this mode. In Figure 14, wireframe mode can be seen.

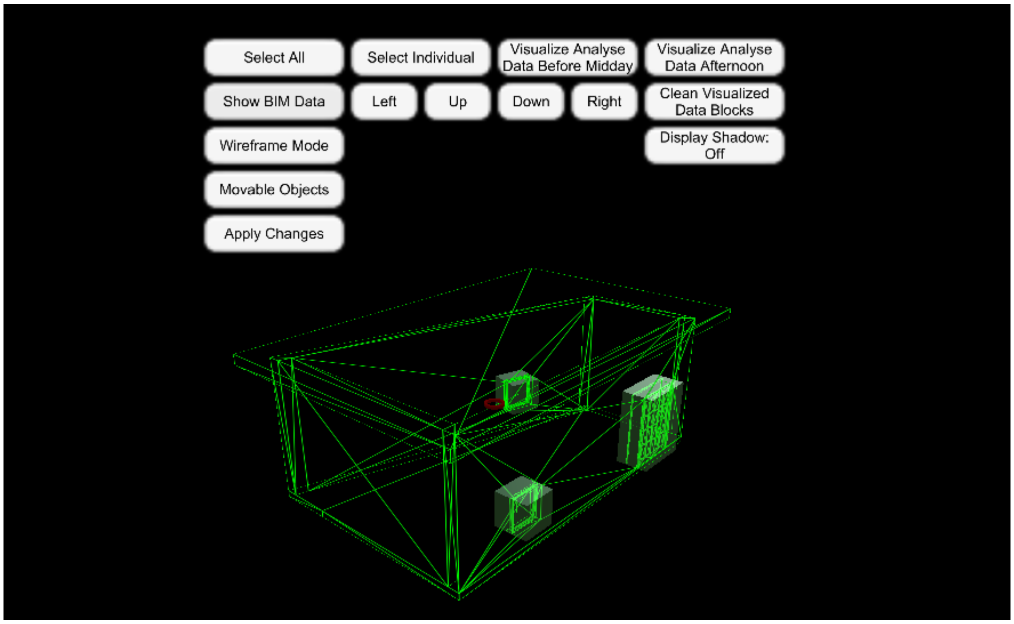

Figure 14: HoloArch project in wireframe mode.

3.3.8. Display Shadow

In this function, users can activate or deactivate shadow simulation. In Autodesk Revit, before daylight analysis, user selects project's coordinates in real world for more realistic analysis. This information is used to calculate sun's position in given date and time. Shadow simulation is an expensive process in computational sense and thus a button is added to activate and deactivate this feature.

3.3.9. Moveable Objects, Material Table and Resize Objects

In this thesis, the main focus is daylight analysis and its effects on the design of buildings for editing purposes. For this purpose, three types of objects for movable objects and two types of objects for material change and resizing are selected. Furniture, trees and shading device's positions, the materials of doors and windows can be changed. These objects are selected since they can alter the daylight analyses results. Users can select the desired furniture or trees or shading device from movable objects' list and place that object by gaze and related interaction method. Unique Autodesk Revit ID cannot be generated out of the program; thus, movable objects must be added to the project scene before they are exported to HoloArch. After users select any door or window from the project, they can change their material from the material lists section and their size in with the resize feature in UI.

CHAPTER 4

SERIOUS GAMES DEVELOPED FOR SPATIAL NAVIGATION IN VIRTUAL AND MIXED REALITY

In this thesis work, two VR- and MR- based games, an action game and a puzzle game, were designed and developed to work as a tutorial for HoloArch in VR and MR environments. In this chapter, these games are presented in detail. In both games, players gaze with moving their heads and interact with objects with either hand gestures or controllers.

4.1. Serious Game No.1: Shape Guardian

Shape Guardian is one of the two games that are designed and developed for this thesis. In this subsection, VR- and MR-based game Shape Guardian is presented in detail.

Shape Guardian is a VR- and MR- based 3D action – shooter game which places the player in the role of a smart defense mechanism against ever-coming rockets. Player's main objective in the game is shooting down enemy rockets while letting ally rockets pass and reach to the player's position. Players need to be precise and fast to be successful in this game.

Shape Guardian is a score-oriented game and the success of the player success is measured by their end game score. Player starts with 10 points, and they gain 5 points for shooting down an enemy rocket or letting an ally rocket pass and reach to the player's position and lose 5 points for shooting down an ally rocket or letting an enemy rocket pass and reach to the player's position.

In a game session, 20 rockets in total spawn and try to reach at player's position. Ally and enemy rocket ratio to the total number of rockets, and their spawning sequence are determined randomly by the script at the start of each game. Rockets spawn on a player-centered top-hemisphere with a 6 m radius. Rockets are programmed to follow and face players all the time. To distinguish between enemy rockets and ally rockets, player needs to focus on the crosshair color—red color is for enemy rockets and green color is for ally rockets. In Figure 15, crosshair's different reactions on enemy rocket and crosshair on ally rocket can be seen.

Shape Guardian game HUD is how player gets important information about the game without breaking his/her game flow. In Figure 15, player's HUD is displayed. In the upper middle part of the HUD, player's current score, remaining number of rockets and time passed since the beginning of the game is available to the player. In the lower right part of the HUD, there is a player centered mini-map located. In this mini-map, rocket's current position according to the player can be seen. In the middle part of the HUD, where player gazes, an animated crosshair appears if there is a rocket in sight. Animation of this crosshair's purpose is to warn the player about upcoming rockets while the color of this crosshair's purpose is to help player to identify whether that is an enemy rocket or an ally rocket.

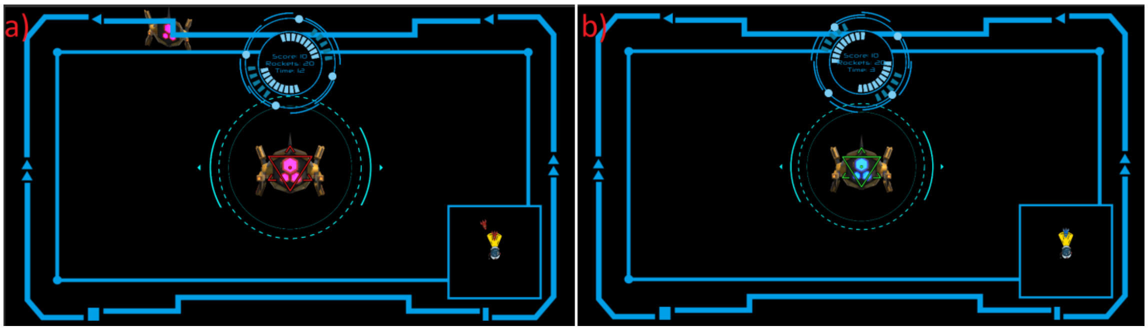

Figure 15: Player HUD crosshair's reaction to a) enemy and b) ally rockets.

If the player's score drops down below zero-point, player loses the game. HUD screen and remaining rockets disappear, and a new HUD screen with an explanatory text of the situation appears. If the player can keep his/her score over zero point until there are no more rockets to interact in the game scene, player wins the game. HUD screen disappears, and a new HUD screen with an explanatory text of the situation appears. Figure 16 shows success/failure flowchart of the Shape Guardian game. In Figure 17, end game HUD screens for success/failure scenarios can be seen.

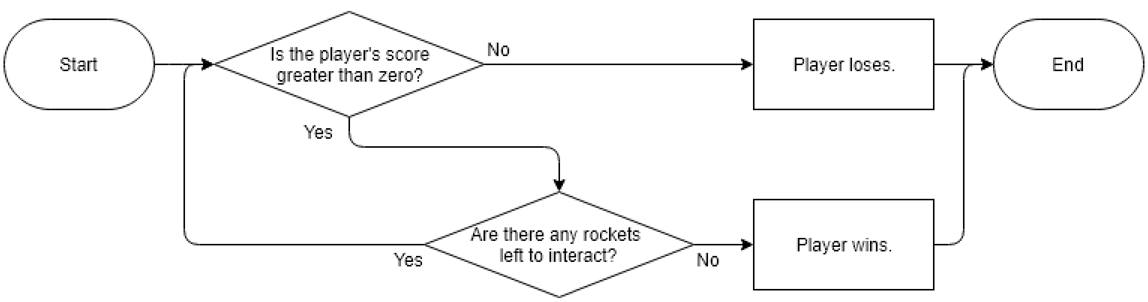

Figure 16: Shape Guardian's success/failure flowchart.

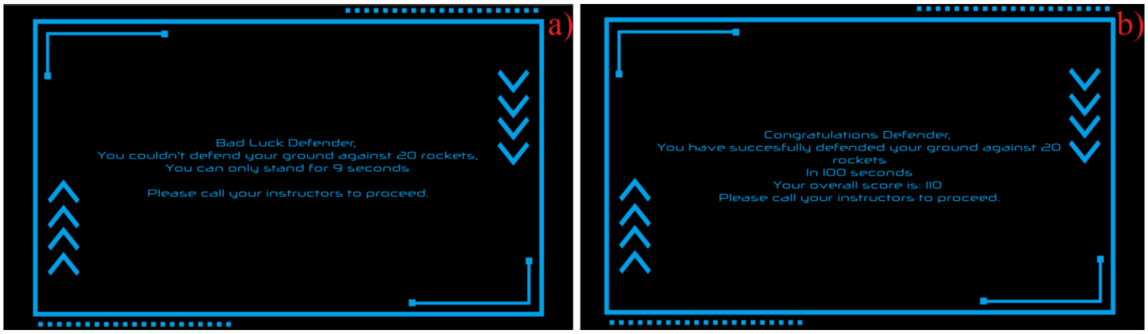

Figure 17: End game HUDs for a) failure scenario and b) success scenario.

4.2. Serious Game No.2: Architects and Buildings

Architects and Buildings is the second game designed and developed for this thesis. In this subsection, VR- and MR- based game Architects and Buildings is presented in detail.

Architects and Buildings is a VR- and MR- based puzzle game. Player's main objectives are solving the given puzzle and advancing to the next level.

Architects and Buildings is a casual puzzle game, solving the puzzle itself is the only goal. It is a grid base game, where a grid tile has four different forms; it can be either an empty tile, a ground tile, an architect tile or a building tile. In Figure 18, four different forms of the grid tile can be seen.

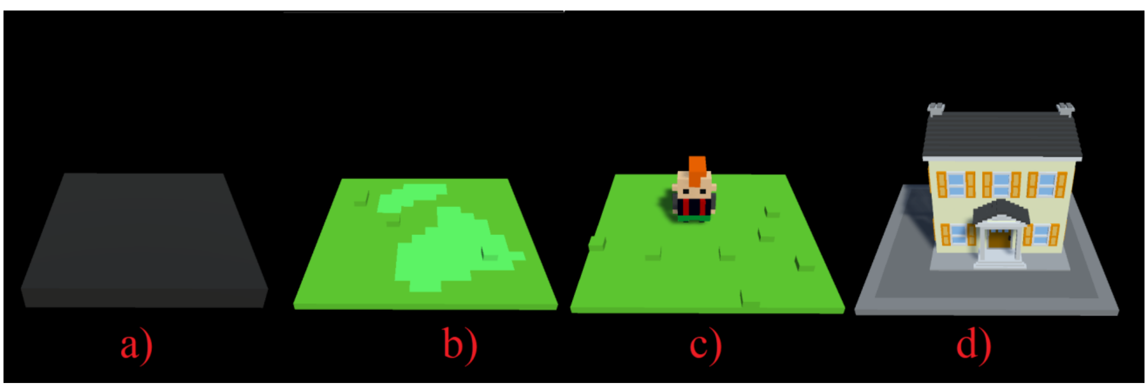

Figure 18: a) Empty, b) Ground, c) Architect and d) Building tiles.

To change the grid tile's form, the player simply gazes on the tile he/she wants to change its form and interact with it. Every time the player interacts with a tile, it changes its current form to the following form. Beginning of the game, all the tiles are either building tiles, building tiles are not open to the player interaction, or empty tiles. Tile interaction order can be seen in Figure 19.

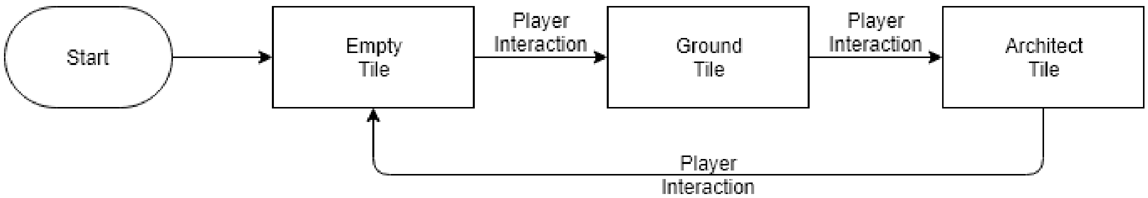

Figure 19: Architects and Buildings' grid tile interaction loop.

To complete a puzzle, player needs to follow the rules above, arrange tiles according to these rules and give the game map its final form.

Rules of the game are as follows:

- Player should place all of the architect in expected places,
- Each architect is assigned to one building (which means there are as many architects as there are buildings),
- Number tiles across the puzzle map indicate how many architects are in that row/column,
- An architect can only be placed horizontally or vertically adjacent to a building,
- Architects shouldn't be placed adjacent to each other; not vertically, horizontally or diagonally,
- A building might be adjacent to two architects, but only one of them counts.

Player can check their progress throughout the level with check button. If all the tiles in a row or in a column is right, number tile responsible to that row or column changes its color to green while if there are one or more wrong tiles in a row or in a column, number tile responsible to that row or a column changes its color to red. Player can check their progress as much as they want. If every tile is in their correct form to solve that puzzle, check button takes the player to the next level. In Figure 20, number tiles in different colors can be seen.

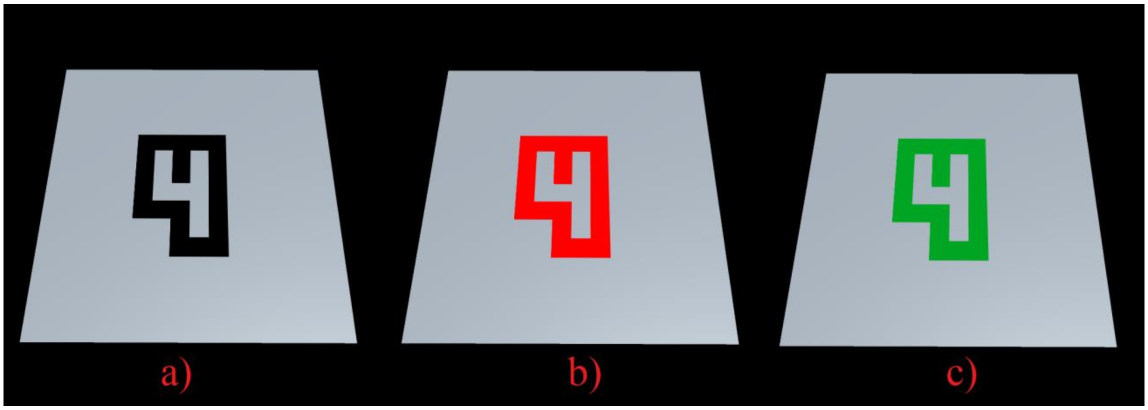

Figure 20: Number tile; a) in its idle form, b) if there is a mistake on the column or row and c) if all the tiles are correct.

Following figures, Figure 19-22, demonstrate screenshots from the Architects and buildings game for better understanding of the game.

Figure 21: User interface of the Main menu.

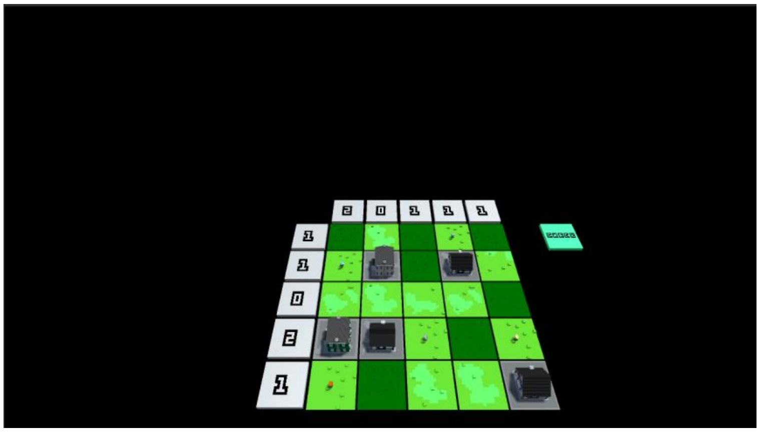

Figure 22: Adjacent squares are solved by the user.

Figure 23: Feedback screen when the user solves the puzzle.

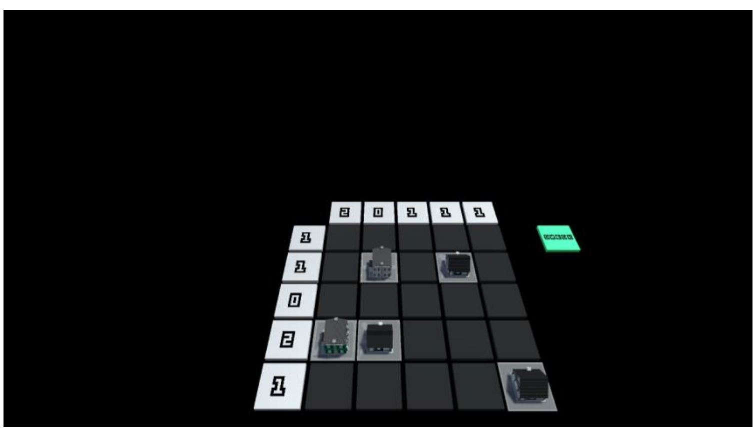

Figure 24: Initial look of the puzzle, the first screen the player sees after starting a new level.

CHAPTER 5

USER STUDIES, WORKSHOP AND EVALUATION

In this chapter, conducted workshops and user studies to evaluate HoloArch tool and games are presented in detail. Three major events (one workshop and two user studies) are organized to evaluate the HoloArch tool and games so that the developed applications can be improved by taking user feedback into consideration.

5.1. Workshop and User Studies

5.1.1. Workshop No.1: Immersive and Responsive Environments Workshop

A two-day workshop was organized for architecture students and architectures to test HoloArch at the Faculty of Architecture of Middle East Technical University between the dates of 23 and 24 November 2018. From workshop applications, 22 participants were recruited to the workshop based on their interest in virtual environments and experience in Autodesk Revit. Participants were either undergraduate or graduate students Faculty of Architecture. The ages of the participants varied from 21 to 30 with an average of 25. Participants' native tongue were Turkish and the workshop was conducted both in Turkish and English. In Figure 24, the poster of Immersive and Responsive Environments Workshop can be seen.

Figure 25: Immersive and Responsive Environments Workshop's poster.

In the first day of the workshop, participants were informed about the general outlines of the workshop, then were lectured on performative mass modelling, daylighting design in architecture and virtual reality in architecture topics. After lectures, 21 students were divided into 5 groups. Group leaders were selected from the most experienced architecture students in Autodesk Revit. Groups were assigned to design an office building for given professions (Doctor, Painter, Carpenter, Florist, Pianist, Tailor, Photographer, and Teacher) in given locations (Ankara (Turkey), Auckland (New Zealand), Dublin (Ireland), Cairo (Egypt) and Reykjavik (Iceland)).

While participants were working on their assignments, they were made familiarized with VR (HTC Vive) and MR (HoloLens) HMD's before testing HoloArch on both devices so that participants could report any issues while testing HMDs and get used to these new environments before using HoloArch tool. Groups finished their projects at the end of the first day and they handed their projects over.

In the second day of the workshop, participants were lectured on BIM and Virtual Environments, and a tutorial on HoloArch tool was given. In this HoloArch tutorial-presentation, participants were informed about the tool's UI, available actions, Autodesk Revit Unity pipeline, HoloArch interactions on HTC Vive (via controllers), and HoloArch interactions on HoloLens (via hand gestures or via a clicker). After the presentations, one project was selected as a pilot project to work on HoloArch visualization and editing tool in VR and MR devices. In Figure 25, participants can be seen while testing HoloArch and attending workshop.

Figure 26: Photographs from Immersive and Responsive Environments Workshop.

During the workshop, participants tested HoloArch tool in four different settings. The differences between settings were kept as minimal as possible. The project and the UI were the same for these four different settings and the only differences were the device used and its user interaction method. These four different settings were as follows:

- HoloArch on HoloLens with gestures: In this setting, participants used gaze and their hands to do gestures and interact with the device and tool. In Figure26a, drawings of a two-hand gesture that is used in this setting, bloom (left) and air tap (right) can be seen.

- HoloArch on HoloLens with a clicker: In this setting, participants used gaze and a little device with one button called clicker instead of gestures to interact with the device and tool. In Figure 26b, drawings of a clicker can be seen.

- HoloArch on HTC Vive with controllers: In this setting, participants used gaze and two controllers to interact with the device and tool. In Figure 26c, a controller can be seen.

- HoloArch on PC (HoloLens Emulator) with a mouse and a keyboard: In these settings, users used mouse movements to simulate the head movement and gaze, left mouse button to simulate air tap gesture, right mouse button to simulate bloom gesture and a keyboard to simulate user’s movement in HoloLens.

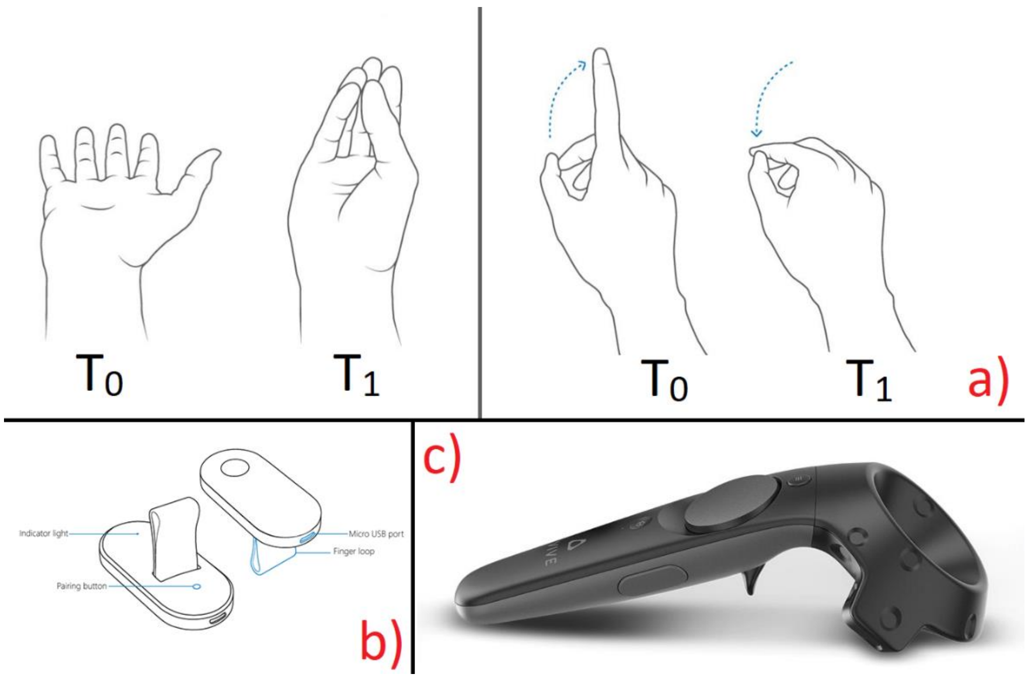

Figure 27: a) Bloom (left) and air tap (right) hand gestures [140], b) HoloLens clicker and its parts [141], c) HTC Vive clicker [142].

Participants tested HoloArch in these four settings in a random order. All participants tested every function in HoloArch before finishing testing tool and they tested the tool between 5 to 15 minutes. After participants finished testing HoloArch, they were asked to fill a 156-question questionnaire with optional comment fields. In the first 132 questions, the same questions were asked both for HTC Vive and HoloLens. The questions were about model interaction and design perception, affordances, participant’s previous experience in Autodesk Revit, participant’s presence state, system usability scale, participant’s immersive tendencies experience and participants technology acceptance model through HoloArch for both HTC Vive and HoloLens. Questionnaires can be seen in Appendix B.

5.1.2. User Study No. 1: HoloArch with Games

A one-day user study for game designers and game enthusiasts to test Shape Guardian, Architects and Buildings games and HoloArch tool was organized on May 3, 2019 at the Informatics Institute of Middle East Technical University. 21 participants attended to this user study. The participants were chosen by their interest in game development and virtual environment tool design. The ages of the participants varied from 24 to 40 with an average of 28. 19 participants' native tongue were Turkish, two participants were fluent in English and the user study was conducted in both Turkish and English. A video game key code was given to those who participated to the user study and completed the questionnaires. In Figure 27, the poster of HoloArch with Games User Study can be seen.

Figure 28: HoloArch with Games User Study no. 1's poster.

Participants were given half an hour appointment for the user study day, arranged by their availabilities beforehand. When participants arrived, brief information about HTC Vive, Microsoft HoloLens, proposed games (i.e. Architectures and Buildings and Shape Guardian) and proposed tool HoloArch, were given. Participants started with either HoloLens with gestures or HTC Vive with controllers. The device order was random and the participants tested the games and the HoloArch tool on both. For both devices, the test order of the applications was the same: Participants started with watching a 30 seconds video recorded in first person point of view in which an architect was designing a project with cardboards, in Figure 28, screenshots from that video can be seen.

Figure 29: Video screenshots in first person view.

One of the things we tested with this video screening was if the participants could see everything clearly in both HMDs. After the video, Shape Guardian game was tested by participants. 19 participants successfully finished the game while two of them failed to do so. Second game, Architects and Buildings was played with its three different levels. Participants were asked to finish the first level if they can, and other two levels were played only if they were willing to keep playing this game. Four participants failed to finish any level, while 12 participants finished the first level and 5 participants chose to finish all three levels. After the games were played by the participants, HoloArch tool was tested by them. In this user study, none of the users were coming from architecture background and none of them used Autodesk Revit software before. To help them to use HoloArch as its full potential, we guided them on what to do and in which order. After a participant finished all the applications in one device, they were asked to do the same procedure for the HMD they didn't try. In Figure 29, participants can be seen while trying proposed games and tool.

Figure 30: Participants experiencing the proposed games and the tool in HoloArch with Games 1 User Study.

Participants tested the games for average of 5 minutes per game and the tool for average of 10 minutes. After participants finished testing the games and HoloArch tool in both HMD devices, they were asked to fill two questionnaires. First one is a 42-question questionnaire with optional comment fields where first 13 questions were related to the gamer's profile. Following 10 questions were System Usability Scale questionnaire about HoloArch and last 19 questions were Technology Acceptance Model questions for both games in both HMD devices. Second one is the same questionnaire set which was used in Immersive and Responsive Environments Workshop. 9 questions had to be discarded since they were about HoloLens with a clicker, HoloLens emulator and previous experience with Autodesk Revit. Questionnaires can be seen in Appendix B.

5.1.3. User Study No. 2: HoloArch with Games

A one-day user study for architecture students at the Faculty of Architecture of Middle East Technical University was organized so that they could test Shape Guardian, Architects and Buildings games and HoloArch tool. 20 participants attended to this user study. The participants were from METU Arch 450 – Generative Design in Architecture [143] class. The ages of the participants varied from 21 to 27 with an average of 24. All participants' native tongue was Turkish and the user study was conducted in both Turkish and English.

Each participant was given a half an hour appointment for the user study day, arranged by her availability beforehand. When participants arrived, brief information about HTC Vive, Microsoft HoloLens, proposed games (i.e. Architectures and Buildings and Shape Guardian) and proposed tool HoloArch, were given. Participants started with either HoloLens with gestures or HTC Vive with controllers. The device order was random and the participants tested them both. For both devices, test order was the same as follows: As in the previous user study, participants started with watching 30 seconds videos recorded in first person point of view in which an architect was designing a project with cardboards—a procedure to check if participants can see everything clearly in both HMDs. After the video, Shape Guardian game was tested by the participants. 17 participants successfully finished the game while three of them failed to finish the game. Second game, Architects and Buildings was tested with its three different levels. The participants were asked to finish the first level if they could and continue with other two levels if they were willing to do so. Six participants failed to finish any level, while 12 participants finished the first level and two participants chose to finish all three levels. After games were played by the participants, they started to test HoloArch tool. When a participant finished all applications in one device, he/she continued to do the same procedure for the HMD he/she didn't try. In Figure 30, participants can be seen while trying proposed games and tool.

Figure 31: Participants experiencing the proposed games and the tool in HoloArch with Games 2 User Study.

Participants tested the games for average of 5 minutes per game and the tool for average of 10 minutes. After participants tested proposed games and tool in both HMD devices, they were asked to fill two questionnaires. First one is a 42-question questionnaire with optional comment fields where first 13 question were on Gamer's Profile. Following 10 questions were from the System Usability Scale questionnaire about HoloArch and last 19 questions were from Technology Acceptance Model questionnaire for both games in both HMD devices. Also, the same 149-question questionnaire with optional comment fields from the Immersive and Responsive Environments Workshop were applied. 7 questions had to be discarded since they were about HoloLens with a clicker and HoloLens emulator. Questionnaires can be seen in Appendix B.

5.2. Evaluation of the Workshop and the User Studies

In all these events, System Usability Scale (SUS) [125], Technology Acceptance Model [120-121], Technology Affordance [144], Presence Questionnaire Item [118] and Immersive Tendency Questionnaire Item [145] questionnaires were answered by the participants to quantify usability, presence and immersion aspects of HoloArch, VR and MR environments and to provide a detailed comparative analysis. Questionnaire given to the participants via e-mail and asked for them to fill the questionnaire according to their user experience as soon as possible.

All the questions of the abovementioned questionnaires are available in Appendix B.

CHAPTER 6

RESULTS

In this chapter, data obtained from the workshop and user studies are analyzed. Throughout this thesis work, one workshop and two user studies were organized so that participant groups from two different disciplines (i.e. architecture and game development) could test developed tool and games and give different insights and detailed feedback on both.

With these questionnaires, the following answers to the following questions were tried to be found:

- Which virtual environment or device fits better for architectural design?
- Can the users' experience of HoloArch be enhanced by introducing tutorial-functioned games to the first-time users beforehand?

In the following tables, workshop and user studies mentioned with their event date instead of their full names; Immersive and Responsive Environments Workshop mentioned as Workshop No. 1, HoloArch with Games User Study 1 mentioned as User Study No. 1 and HoloArch with Games User Study 2 mentioned as User Study No. 2.

Design Perception Questionnaire

There are six questions per virtual environment device in Design Perception Questionnaire about HoloArch tool. Questionnaire's results can be seen in Table 2. These questions were designed to understand users' point of view on how positive their experience with developed tool HoloArch.

Table 2: Design Perception Questionnaire — Mean and standard deviation results of workshop and user studies. Answers of the questionnaire are on a 1 to 7 scale; higher score indicates a more positive attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	5.01 ± 0.3	5.31 ± 0.3	4.53 ± 0.4
HTC Vive	5.33 ± 0.6	5.15 ± 0.5	4.88 ± 0.8

Affordances Questionnaire

There are four questions per virtual environment devices in Affordances Questionnaire about HoloArch tool. Questionnaire's results (i.e. mean and standard deviation values) can be seen in Table 3. These questions were designed to understand users' point of view on how beneficial the developed tool HoloArch for them.

Table 3: Affordances Questionnaire — Mean and standard deviation results of workshop and user studies for HoloArch tool. Questionnaire's answers are on a 1 to 7 scale; higher score indicates a more positive attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	5.11 ± 0.4	5.07 ± 0.3	4.75 ± 0.2
HTC Vive	5.25 ± 0.5	4.82 ± 0.4	4.65 ± 0.3

Tool Competence Questionnaire

There are three questions per virtual environment devices in Tool Competence Questionnaire about HoloArch tool. Questionnaire's results can be seen in Table 4. These questions were designed to understand participants' previous experiences on Autodesk Revit, daylight analysis and immersive virtual environments.

Table 4: Tool Competence Questionnaire — Mean and standard deviation results of workshop and user studies for HoloArch tool. Answers of the questionnaire are on a 1 to 7 scale; higher score indicates a more positive attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	3.94 ± 0.6	3.16 ± 0.9	4.80 ± 0.6
HTC Vive	4.21 ± 0.4	3.21 ± 1.1	4.93 ± 0.4

Presence Questionnaire

There are 27 questions per virtual environment devices in Presence Questionnaire about HoloArch tool. Questionnaire's results can be seen in Table 5 and Table 6. Presence questionnaire were used to evaluate participants level of presence with developed tool HoloArch.

Table 5: Presence Questionnaire — Mean and standard deviation results of workshop and user studies on positive statements for HoloArch tool. Answers of the questionnaires are on a 1 to 7 scale; higher score indicates a more positive attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	4.71 ± 0.4	5.12 ± 0.4	4.39 ± 0.5
HTC Vive	5.19 ± 0.5	5.36 ± 0.6	4.89 ± 0.6

Table 6: Presence Questionnaire — Mean and standard deviation results of workshop and user studies on negative statements for HoloArch tool. Answers of the questionnaire are on a 1 to 7 scale; higher score indicates a more negative attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	4.18 ± 0.3	4.26 ± 0.6	4.49 ± 0.4
HTC Vive	4.66 ± 0.4	3.86 ± 0.6	3.92 ± 0.5

System Usability Scale Questionnaire

There are 10 questions per virtual environment device in System Usability Scale Questionnaire about HoloArch tool. Questionnaire's results can be seen in Table 7 and Table 8. SUS questionnaire used to see how usable our developed tool HoloArch.

Table 7: System Usability Scale Questionnaire — Mean and standard deviation results of workshop and user studies on positive statements for HoloArch tool. Answers of the questionnaire are on a 1 to 5 scale; higher score indicates a more positive attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	3.62 ± 0.2	3.81 ± 0.3	3.85 ± 0.3
HTC Vive	4.23 ± 0.3	4.24 ± 0.3	4.41 ± 0.2

Table 8: System Usability Scale Questionnaire — Mean and standard deviation results of workshop and user studies on negative statements for HoloArch tool. Answers of the questionnaire are on a 1 to 5 scale; higher score indicates a more negative attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	2.47 ± 0.5	2.27 ± 0.1	2.58 ± 0.4
HTC Vive	2.05 ± 0.4	2.12 ± 0.1	2.37 ± 0.5

Immersive Tendency Questionnaire

There are 14 questions per virtual environment device in Immersive Tendency Questionnaire about HoloArch tool. Questionnaire's results can be seen in Table 9. These questions were used to understand participants' degree of immersion during the testing of developed tool HoloArch. There is a positive correlation between degree of immersion and presence.

Table 9: Immersive Tendency Questionnaire — Mean and standard deviation results of workshop and user studies for HoloArch tool. Questionnaires answers are on a 1 to 7 scale; higher score indicates a more positive attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	4.76 ± 0.9	4.51 ± 0.7	5.05 ± 0.6
HTC Vive	4.78 ± 0.9	4.57 ± 0.7	5.06 ± 0.7

Technology Acceptance Model Questionnaire

There are 15 questions per virtual environment device in Technology Acceptance Model Questionnaire about HoloArch tool and 38 questions (nineteen per game) per virtual device in TAM Questionnaire about Shape Guardian and Architects and buildings games. Questionnaire results can be seen in Table 10, Table 11 and Table 12. TAM questionnaire used to understand participants acceptance level of the proposed systems and usage of the systems.

Table 10: Technology Acceptance Model Questionnaire — Mean and standard deviation results of workshop and user studies on positive statements for HoloArch tool. Answers of the questionnaire are on a 1 to 10 scale; higher score indicates a more positive attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	7.10 ± 1.0	6.81 ± 0.5	6.99 ± 0.6
HTC Vive	7.74 ± 1.0	7.19 ± 0.5	7.25 ± 0.6

Table 11: Technology Acceptance Model Questionnaires — Mean and standard deviation results of workshop and user studies on negative statements for HoloArch tool. Answers of the questionnaire are on a 1 to 10 scale; higher score indicates a more negative attitude.

	Workshop No. 1	User Study No. 1	User Study No. 2
HoloLens	3.24 ± 2.7	3.71 ± 2.8	3.73 ± 2.6
HTC Vive	3.10 ± 3.1	2.95 ± 2.6	2.47 ± 1.5

Table 12: Technology Acceptance Model Questionnaire — Mean and standard deviation results of workshop and user studies on both positive and negative statements for Shape Guardian and Architects and Buildings games. Answers of the questionnaire are on a 0 to 10 scale; higher score indicates a more positive attitude in positive statement questions and a more negative attitude in negative statement questions.

		User Study No. 1		User Study No. 2	
		Positive Statements	Negative Statements	Positive Statements	Negative Statements
HoloLens	Shape Guardian	8.25 ± 1.1	1.19 ± 1.4	7.87 ± 1.0	2.42 ± 2.7
	Architects and Buildings	7.88 ± 1.2	1.33 ± 1.5	7.72 ± 0.9	2.79 ± 2.5
HTC Vive	Shape Guardian	8.54 ± 1.1	1.24 ± 1.8	8.58 ± 0.6	1.79 ± 2.5
	Architects and Buildings	8.36 ± 1.2	1.10 ± 1.8	8.36 ± 0.8	2.26 ± 2.9

Questions on Measuring the Impact of the Games

In the questionnaires, there are 16 questions (8 for HoloLens and 8 for HTC Vive) in four different sections to measure if the games satisfied their purposes. Next four tables are display these questions, their mean and standard deviation results and its questionnaire overall mean and standard deviation results.

Table 13: Design Perception Questionnaire — Overall mean and standard deviation and selected questions which evaluate how easily a participant learns to use the developed tool. Answers of the questionnaire are on a 1 to 7 scale; higher score indicates a more positive attitude.

	HMD	Workshop No. 1	User Study No. 1	User Study No. 2
Design Perception Questionnaire Overall.	HoloLens	5.01 ± 0.3	5.31 ± 0.3	4.53 ± 0.4
	HTC Vive	5.33 ± 0.6	5.15 ± 0.5	4.88 ± 0.8
Design Perception How easy was it for you to navigate (move) in your design in the virtual environment?	HoloLens	4.52 ± 1.8	5.05 ± 1.5	4.60 ± 1.7
	HTC Vive	5.24 ± 1.3	5.40 ± 1.8	5.80 ± 1.6

Table 14: Presence Questionnaire — Overall mean and standard deviation and selected questions which evaluate how easily a participant learns to use the developed tool. Questionnaires answers are on a 1 to 7 scale; higher score indicates a more positive attitude.

	HMD	Workshop No. 1	User Study No. 1	User Study No. 2
Presence Questionnaire (Positive Statements) Overall.	HoloLens	4.71 ± 0.4	5.12 ± 0.4	4.39 ± 0.5
	HTC Vive	5.19 ± 0.5	5.36 ± 0.6	4.89 ± 0.6
Presence (Positive Statements) How responsive was the environment to actions that you initiated (or performed)?	HoloLens	4.76 ± 1.3	4.95 ± 1.8	4.40 ± 1.7
	HTC Vive	5.48 ± 1.1	5.76 ± 1.4	5.53 ± 1.2
Presence (Positive Statements)	HoloLens	4.76 ± 1.7	4.90 ± 1.7	4.20 ± 1.6

How natural was the mechanism which controlled movement through the environment?	HTC Vive	4.67 ± 1.3	4.81 ± 1.7	4.73 ± 1.2
Presence (Positive Statements) How easily did you adjust to the control devices used to interact with the virtual environment?	HoloLens	4.57 ± 1.7	4.67 ± 1.7	4.93 ± 1.4
	HTC Vive	5.67 ± 1.6	6.24 ± 1.2	5.87 ± 1.4

Table 15: System Usability Scale Questionnaire — Overall mean and standard deviation and selected questions which evaluate how easily a participant learns to use the developed tool. Answers of the questionnaires are on a 1 to 5 scale; higher score indicates a more positive attitude.

	HMD	Workshop No. 1	User Study No. 1	User Study No. 2
System Usability Scale (Positive Statements) Overall.	HoloLens	3.62 ± 0.2	3.81 ± 0.3	3.85 ± 0.3
	HTC Vive	4.23 ± 0.3	4.24 ± 0.3	4.41 ± 0.2
System Usability Scale (Positive Statements) I thought the system was easy to use.	HoloLens	3.52 ± 1.3	3.90 ± 0.9	3.80 ± 1.3
	HTC Vive	4.48 ± 0.6	4.38 ± 0.9	4.53 ± 0.6
System Usability Scale (Positive Statements) I would imagine that most people would learn to use this system very quickly.	HoloLens	3.29 ± 1.3	3.62 ± 1.1	3.47 ± 1.5
	HTC Vive	4.05 ± 0.9	4.10 ± 1.1	4.53 ± 0.8

Table 16: System Usability Scale Questionnaire — Overall mean and standard deviation and selected questions which aim to evaluate how easily a participant learns to use the developed tool. Answers of the questionnaires are on a 1 to 5 scale; higher score indicates a more negative attitude.

	HMD	Workshop No. 1	User Study No. 1	User Study No. 2
System Usability Scale (Negative	HoloLens	2.47 ± 0.5	2.27 ± 0.1	2.58 ± 0.4

Statements) Overall.	HTC Vive	2.05 ± 0.4	2.12 ± 0.1	2.37 ± 0.5
System Usability Scale (Negative Statements) I needed to learn a lot of things before I could get going with this system.	HoloLens	2.76 ± 1.4	2.24 ± 1.3	2.53 ± 1.3
	HTC Vive	2.14 ± 1.2	2.05 ± 1.3	1.93 ± 1.1

Table 17: Technology Acceptance Model Questionnaire — Overall mean and standard deviation and selected questions which aim to evaluate how easily a participant learns to use the developed tool. Answers of the questionnaires are on a 1 to 10 scale; higher score indicates a more positive attitude.

	HMD	Workshop No. 1	User Study No. 1	User Study No. 2
Technology Acceptance Model (Positive Statements) Overall.	HoloLens	7.10 ± 1.0	6.81 ± 0.5	6.99 ± 0.6
	HTC Vive	7.74 ± 1.0	7.19 ± 0.5	7.25 ± 0.6
Technology Acceptance Model (Positive Statements) I did not find it hard to interact with the virtual world.	HoloLens	7.81 ± 1.8	7.81 ± 1.8	8.00 ± 2.1
	HTC Vive	7.81 ± 1.8	7.81 ± 1.8	8.00 ± 2.1

CHAPTER 7

DISCUSSION

In this chapter, the data obtained from the workshop and two user studies are discussed in detail.

The results of questionnaires and our observations on the users show that presented tool HoloArch was found satisfactory in terms of presence, system usability and technology acceptance model for both VR and MR environments. In these sections, participants' answers' mean values were higher than average in positive statements and lower than average in negative statements. Statement "I would like to keep using this system in the future" gets a 9.19 (Immersive and Responsive Environments Workshop) and 8.13 (HoloArch with Games User Study 2) mean score on a 10-point Likert scale (1 being the most negative) by architects and architecture students.

One of the aims of this thesis work is to provide an easier-to-understand 3D visualization of complex 2D analysis data (i.e. daylight analysis data) for the users of the HoloArch tool. Design perception and affordances results show that HoloArch's 3D visualization of Revit's daylight analysis achieves this objective. Question "How easy was it to perceive and understand the simulation results in the virtual environment?" in design perception section of the questionnaire and the question "How much benefit did you get from the visualization of the simulation results?" in affordances section of the questionnaire were specifically designed to answer this research question. For both HMDs in the workshop and user studies, participants' responses were over 4.5 on a 7-point Likert scale (1 being the most negative) by both architects and game designers.

Another objective of this thesis work is to examine and compare VR and MR environments from an architectural design perspective. Developed tool HoloArch was designed in a way to satisfy this purpose in which interaction methods, tool workflow, visual and auditory assets were kept the same between VR and MR environments for a clearer comparison. Questionnaire data clearly indicate that the majority of the users prefers VR environment over MR environment for architectural design. HoloArch tool on HTC Vive gets higher mean scores compared to HoloArch tool on HoloLens in every section of the questionnaire in Immersive and Responsive Environments Workshop and HoloArch with Games User Study 2. In HoloArch with Games User Study 1, HoloArch tool on HoloLens gets higher mean scores in design perception and affordances sections, but this can be explained with user study participants' familiarity with HTC Vive device and curiosity over Microsoft HoloLens. Majority of the HoloArch with Games User Study 1 participants were developing applications and games on various virtual environments (mostly on commercial devices), and one of their main purposes to participate in this user study was to try and experience the Microsoft HoloLens device.

In Immersive and Responsive Environments Workshop, users tried HoloArch tool on four different settings; HTC Vive with two controllers, HoloLens with gestures, HoloLens with a clicker and HoloLens emulator on computer with a keyboard and a mouse. In TAM section of the questionnaire, the following questions were asked to the participants: “I liked training with the HTC Vive and controllers”, “I liked the training with the HoloLens using gestures”, “I liked the training with the HoloLens using the clicker”, “I liked the training with the HoloLens using the emulator” and the answers scored on a 10-point Likert scale (1 being the most negative). The mean values of participants answers were 9.10, 7.81, 7.33 and 4.90, respectively.

On the last two user studies, the main research question is: “Could playing specifically designed video games on newly introduced technologies beforehand help the users?”. To answer this question, two games with different genres were introduced which were designed with the same interaction methods with HoloArch tool and were compared with the Immersive and Responsive Environments Workshop’s results. Even though there is not a significant difference in the participants’ questionnaire answers on HoloArch with Games no. 1 and HoloArch with Games no. 2 User Studies when compared to Immersive and Responsive Environments Workshop, observations on the users while testing HoloArch show that the participants who played proposed games beforehand had asked less questions during the intervention and had less problems while interacting with HoloArch in both HMDs.

Questions and the answers of Table 13 show that the games were successful as tutorial to both HoloArch and newly introduced digital design environments. In Table 13, aforementioned questions, their answer means and overall section means are shown. These 16 questions (8 for HoloLens and 8 for HTC Vive) in four different sections of the questionnaire were asked to the participants in Immersive and Responsive Environments Workshop, HoloArch with Games User Study no. 1 and HoloArch with Games User Study no. 2. They were helpful in understanding if the proposed games fulfilled their purpose of improving participants’ comprehension of newly introduced technologies. In 13 out of 16 questions, participants who played games before using the proposed tool had answered more favorable to the questions in both user studies than participants who didn’t play the games in advance. In the three remaining questions, participants who played games before using the proposed tool had answered more favorable to the questions in one user study than participants who did not play the games in advance.

CHAPTER 8

CONCLUSION AND FUTURE WORK

In this thesis work, a VR- and MR- based architectural visualization and editing tool HoloArch [146-148] and two VR- and MR- based serious games, Shape Guardian and Architects and Buildings, are developed. HoloArch tool allows its users to visualize their Autodesk Revit projects in VR and MR environments, visualize daylight analysis data in a more user-friendly 3D graph, edit pre-selected features of their project and transfer those changes to Autodesk Revit when needed. Shape Guardian and Architects and Buildings games are developed to serve as subtle tutorials for VR and MR environments before using the HoloArch tool.

A workshop to test HoloArch and two user studies were conducted to test HoloArch tool and Shape Guardian and Architects and Buildings games were conducted at Middle East Technical University. The workshop was held at the Faculty of Architecture with 21 participants, who were selected amongst architects and architecture students. First user study was held at Informatics Institute with 21 participants who were selected amongst game developers and computer science majors. Last user study was held at the Faculty of Architecture with 20 participants who were selected amongst architects and architecture students. Questionnaires, oral questions, blank suggestion fields and participant observations were used to evaluate the HoloArch tool and two serious games.

The results show that HoloArch tool in VR environment was preferred over HoloArch tool in MR environment and proposed video games help users with the newly introduced technologies.

User feedbacks show that the following improvements and extensions can be made as future work:

- The BIM data visualization can be improved in HoloArch,

- The daylight analysis data can be updated during runtime in the HoloArch,

- HoloArch's UI can be improved and changed to suit better the architects' expectations. Making the UI more similar to Autodesk Revit would be the direction to take. User feedbacks from the workshop and the user studies show that user expectations for the tools' UI were similar in design with Autodesk Revit,

- Materials and textures of project models can be added to HoloArch. In this thesis work, HoloArch did not support importing visual material and texture data from

Autodesk Revit. In the workshop and the user studies, it was observed that this situation was one of the most common improvement suggestions,

- Serious games with new genres and additional difficulty levels can be added to improve the user experience.

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APPENDICES

APPENDIX A

The advantages and disadvantages of different file export methods

Export Method	Advantages	Disadvantages
Autodesk Revit's export method	• Game object names contain their unique BIM IDs. • Element meshes are separated properly. • Game objects have materials with correct names.	Textures are missing.
Archilizer fbx exporter	• Game object names contain their unique BIM IDs. • Element meshes are separated properly.	• Textures are missing. • Game object materials are missing.
SimLab fbx exporter	Element meshes are separated properly.	• Textures are missing. • Game object names do not hold their unique BIM IDs. • Game object materials are missing.
CTC BIM batch suite	• Game object names contain	Textures are missing.

	their unique BIM IDs. • Element meshes are separated properly.	Game object materials are missing.
Twin motion exporter (with group by dummy settings)	None	• Textures are missing. • Game object names do not contain their unique BIM IDs. • Game object materials are missing. • Game object meshes are missing. • Error occurs while importing the project to Unity.
Twin motion exporter (with group by family settings)	Game objects have materials with right names.	• Textures are missing. • Game objects name don't contain their unique BIM ID. • Error occurs while importing project to Unity. • Elements meshes are not separated properly.
Twin motion exporter (with group by material settings)	Game objects have materials with right names.	• Textures are missing. • Game objects name do not contain their unique BIM IDs. • Error occurs while

		importing the project to Unity. • Element meshes are not separated properly.
Twin motion exporter (without any selected settings)	• Element meshes are separated properly. • Game objects have materials with correct names.	• Textures are missing. • Game objects name do not contain their unique BIM IDs. • Error occurs while importing the project to Unity.
Twin motion exporter (with group by type settings)	Element meshes are separated properly.	• Textures are missing. • Game object materials are missing. • Game objects name do not contain their unique BIM IDs. • Error occurs while importing the project to Unity.

APPENDIX B

QUESTIONNAIRES – PRESENCE

Presence in HTC Vive (Answers from 1 to 7, 1 being most negative)	
HTC Vive (1 to 7)	How much delay did you experience between your actions and expected outcomes?
	How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?
	How much did the control devices interfere with the performance of assigned tasks or with other activities?
	To what extent did events occurring outside the virtual environment distract from your experience in the virtual environment?
	Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?
Presence in HoloLens (Answers from 1 to 7, 1 being most negative)	
HoloLens (1 to 7)	How much delay did you experience between your actions and expected outcomes?
	How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?
	How much did the control devices interfere with the performance of assigned tasks or with other activities?
	To what extent did events occurring outside the virtual environment distract from your experience in the virtual environment?
	Overall, how much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?
Presence in HTC Vive (Answers from 1 to 7, 1 being most negative)	
HTC Vive (1 to 7)	How much were you able to control events?
	How responsive was the environment to actions that you initiated (or

	performed)?
	How natural did your interactions with the environment seem?
	How much did the visual aspects of the environment involve you?
	How natural was the mechanism which controlled movement through the environment?
	How compelling was your sense of objects moving through space?
	How much did your experiences in the virtual environment seem consistent with your real-world experiences?
	Were you able to anticipate what would happen next in response to the actions that you performed?
	How completely were you able to actively survey or search the environment using vision?
	How well could you actively survey or search the virtual environment using touch?
	How compelling was your sense of moving around inside the virtual environment?
	How closely were you able to examine objects?
	How well could you examine objects from multiple viewpoints?
	How well could you move or manipulate objects in the virtual environment?
	How involved were you in the virtual environment experience?
	How quickly did you adjust to the virtual environment experience?
	How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
	How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
	How completely were your senses engaged in this experience?
	Were you involved in the experimental task to the extent that you lost track

	of time?
	How easy was it to identify objects through physical interaction, like touching an object, walking over a surface, or bumping into a wall or object?
	Were there moments during the virtual environment experience when you felt completely focused on the task or environment?
	How easily did you adjust to the control devices used to interact with the virtual environment?
Presence in HoloLens (Answers from 1 to 7, 1 being most negative)	
HoloLens (1 to 7)	How much were you able to control events?
	How responsive was the environment to actions that you initiated (or performed)?
	How natural did your interactions with the environment seem?
	How much did the visual aspects of the environment involve you?
	How natural was the mechanism which controlled movement through the environment?
	How compelling was your sense of objects moving through space?
	How much did your experiences in the virtual environment seem consistent with your real-world experiences?
	Were you able to anticipate what would happen next in response to the actions that you performed?
	How completely were you able to actively survey or search the environment using vision?
	How well could you actively survey or search the virtual environment using touch?
	How compelling was your sense of moving around inside the virtual environment?
	How closely were you able to examine objects?

	How well could you examine objects from multiple viewpoints?
	How well could you move or manipulate objects in the virtual environment?
	How involved were you in the virtual environment experience?
	How quickly did you adjust to the virtual environment experience?
	How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
	How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?
	How completely were your senses engaged in this experience?
	Were you involved in the experimental task to the extent that you lost track of time?
	How easy was it to identify objects through physical interaction, like touching an object, walking over a surface, or bumping into a wall or object?
	Were there moments during the virtual environment experience when you felt completely focused on the task or environment?
	How easily did you adjust to the control devices used to interact with the virtual environment?

QUESTIONNAIRES – TECHNOLOGY ACCEPTANCE MODEL

<table>
<tr><td colspan="2">Technology Acceptance Model (Answers from 1 to 10, 1 being most negative)</td></tr>
<tr><td>HTC Vive 1 to 10</td><td>During the interaction using HTC Vice, I felt pain and/or discomfort.</td></tr>
<tr><td colspan="2">Technology Acceptance Model (Answers from 1 to 10, 1 being most negative)</td></tr>
<tr><td>HoloLens 1 to 10</td><td>During the interaction using HoloLens, I felt pain and/or discomfort.</td></tr>
<tr><td colspan="2">Technology Acceptance Model (Answers from 1 to 10, 1 being most negative)</td></tr>
<tr><td rowspan="12">HTC Vive 1 to 10</td><td>I liked training with the HTC Vive and controllers</td></tr>
<tr><td>The environment was challenging and fun.</td></tr>
<tr><td>It’s easy to interact with the environment HTC Vive)</td></tr>
<tr><td>The UI reacts readily to my movements (HTC Vive)</td></tr>
<tr><td>I did not find it hard to interact with the virtual world.</td></tr>
<tr><td>I found the graphical interface clear and explanatory.</td></tr>
<tr><td>The sound effects are useful, the sound created when I click a button is useful to understand what I am doing.</td></tr>
<tr><td>I liked the interface design. (Any advice on how to improve it?)</td></tr>
<tr><td>The instructions of the UI are clear. I understood what to do in the UI and how.</td></tr>
<tr><td>The sound effects are useful, the sound created when I click a button is useful to understand what I am doing.</td></tr>
<tr><td>The visual signals that appear when I click a button is useful.</td></tr>
<tr><td>The virtual headset is big and close enough (HTC Vive)</td></tr>
</table>

	I would like to keep using with this system in the future.
	If I had the option to keep using the system at home, I would use it often using HTC Vive and controllers
Technology Acceptance Model (Answers from 1 to 10, 1 being most negative)	
HoloLens 1 to 10	liked the training with the HoloLens using gestures
	liked the training with the HoloLens using the clicker
	liked the training with the HoloLens using the emulator
	The environment was challenging and fun.
	It's easy to interact with the environment (HoloLens)
	The UI reacts readily to my movements (HoloLens)
	I did not find it hard to interact with the virtual world.
	I found the graphical interface clear and explanatory.
	The sound effects are useful, the sound created when I click a button is useful to understand what I am doing.
	I liked the interface design. (Any advice on how to improve it?)
	The instructions of the UI are clear. I understood what to do in the UI and how.
	The sound effects are useful, the sound created when I click a button is useful to understand what I am doing.
	The visual signals that appear when I click a button is useful.
	The virtual headset is big and close enough (HoloLens)
	I would like to keep using with this system in the future.
	If I had the option to keep using the system at home, I would use it often using HoloLens with gestures.
	If I had the option to keep using the system at home, I would use it often using HoloLens with a clicker.

QUESTIONNAIRES – SYSTEM USABILITY SCALE

System Usability Scale in HTC Vive (1: Strongly Disagree 5: Strongly Agree)	
HTC Vive (1 to 5)	I found the system unnecessarily complex.
	I think that I would need the support of a technical person to be able to use this system.
	I thought there was too much inconsistency in this system.
	I found the system very cumbersome to use.
	I needed to learn a lot of things before I could get going with this system.
System Usability Scale in HoloLens (1: Strongly Disagree 5: Strongly Agree)	
HoloLens (1 to 5)	I found the system unnecessarily complex.
	I think that I would need the support of a technical person to be able to use this system.
	I thought there was too much inconsistency in this system.
	I found the system very cumbersome to use.
	I needed to learn a lot of things before I could get going with this system.
System Usability Scale in HTC Vive (1: Strongly Disagree 5: Strongly Agree)	
HTC Vive (1 to 5)	I think that I would like to use this system frequently.
	I thought the system was easy to use.
	I found the various functions in this system were well integrated.
	I would imagine that most people would learn to use this system very quickly.
	I felt very confident using the system.

System Usability Scale in HoloLens (1: Strongly Disagree 5: Strongly Agree)	
HoloLens (1 to 5)	I think that I would like to use this system frequently.
	I thought the system was easy to use.
	I found the various functions in this system were well integrated.
	I would imagine that most people would learn to use this system very quickly.
	I felt very confident using the system.

QUESTIONNAIRES – DESIGN PERCEPTION, AFFORDANCES AND TOOL COMPETENCE

Design Perception in HTC Vive (Answers from 1 to 7, 1 being most negative)	
HTC Vive (1 to 7)	how easy was it for you to navigate (move) in your design in the virtual environment?
	how did the architectural scaling operation affect your design perception?
	which scale was most appropriate during your design process?
	how easy was it for you to perceive the visual features of your building (physical building elements) design in the virtual environment?
	how easy was it for you to perceive the spaces and spatial relationships in your building design in the virtual environment?
	how realistic was your design in the virtual environment as compared to the real life?
	how was your presence in the environment as compared to Revit?
	how easy was it to perceive and understand the simulation results in the virtual environment?
Design Perception in HoloLens (Answers from 1 to 7, 1 being most negative)	
HoloLens (1 to 7)	how easy was it for you to navigate (move) in your design in the virtual environment?
	how did the architectural scaling operation affect your design perception?
	which scale was most appropriate during your design process?
	how easy was it for you to perceive the visual features of your building (physical building elements) design in the virtual environment?
	how easy was it for you to perceive the spaces and spatial relationships in your building design in the virtual environment?
	how realistic was your design in the virtual environment as compared to the real life?

	how was your presence in the environment as compared to Revit?
	how easy was it to perceive and understand the simulation results in the virtual environment?
Affordances in HTC Vive (Answers from 1 to 7, 1 being most negative)	
HTC Vive (1 to 7)	How much benefit did you get from the visualization of the building design geometry?
	How much benefit did you get from the visualization of the BIM component data?
	How much benefit did you get from the visualization of the simulation results?
	Did the visualization of the building simulation result improve your perception on building daylighting performance?
Affordances in HoloLens (Answers from 1 to 7, 1 being most negative)	
HoloLens (1 to 7)	How much benefit did you get from the visualization of the building design geometry?
	How much benefit did you get from the visualization of the BIM component data?
	How much benefit did you get from the visualization of the simulation results?
	Did the visualization of the building simulation result improve your perception on building daylighting performance?
Tool Competence in HTC Vive (Answers from 1 to 7, 1 being most negative)	
HTC Vive (1 to 7)	What was previous experience with Revit?
	What was previous experience with daylighting simulation?
	What was previous experience with immersive virtual environments (Virtual Reality, Mixed Reality, Augmented Reality)?
Tool Competence in HoloLens (Answers from 1 to 7, 1 being most negative)	
HoloLens	What was previous experience with Revit?

(1 to 7)	What was previous experience with daylighting simulation?
	What was previous experience with immersive virtual environments (Virtual Reality, Mixed Reality, Augmented Reality)?

QUESTIONNAIRE – IMMERSIVE TENDENCY QUESTIONNAIRE ITEM

Immersive Tendency Questionnaire Item (Answers from 1 to 7, 1 being most negative)	
HTC Vive (1 to 7)	Do you ever get extremely involved in projects that are assigned to you by your boss or your instructor, to the exclusion of other tasks?
	How easily can you switch your attention from the task in which you are currently involved to a new task?
	How frequently do you get emotionally involved (angry, sad, or happy) in the news stories that you read or hear?
	How well do you feel today?
	Do you easily become deeply involved in movies or TV dramas?
	Do you ever become so involved in a television program or book that people have problems getting your attention?
	How mentally alert do you feel at the present time?
	Do you ever become so involved in a movie that you are not aware of things happening around you?
	How frequently do you find yourself closely identifying with the characters in a story line?
	Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?
	Are you easily disturbed when working on a task
	How well do you concentrate on enjoyable activities?
	How often do you play arcade or video games? (OFTEN should be taken to mean every day or every two days, on average.)
	Do you ever become so involved in doing something that you lose all track of time?
Immersive Tendency Questionnaire Item (Answers from 1 to 7, 1 being most negative)	
HoloLens	Do you ever get extremely involved in projects that are assigned to you by

(1 to 7)	your boss or your instructor, to the exclusion of other tasks?
	How easily can you switch your attention from the task in which you are currently involved to a new task?
	How frequently do you get emotionally involved (angry, sad, or happy) in the news stories that you read or hear?
	How well do you feel today?
	Do you easily become deeply involved in movies or TV dramas?
	Do you ever become so involved in a television program or book that people have problems getting your attention?
	How mentally alert do you feel at the present time?
	Do you ever become so involved in a movie that you are not aware of things happening around you?
	How frequently do you find yourself closely identifying with the characters in a story line?
	Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?
	Are you easily disturbed when working on a task
	How well do you concentrate on enjoyable activities?
	How often do you play arcade or video games? (OFTEN should be taken to mean every day or every two days, on average.)
	Do you ever become so involved in doing something that you lose all track of time?

QUESTIONS – SUGGESTIONS

Suggestions on the System	
	What are your suggestions for us to improve the UI?
	What are your suggestions for us to improve the experience with HTC Vive?
	What are your suggestions for us to improve the experience with HoloLens?
	Which interaction type did you enjoy the most; mixed reality or virtual reality? Why?
	What are the main strengths of the current system? Please explain.
	What are the main flaws of the current system? Please explain.
	Which additional functionalities will be useful to improve the system?
	Insert here all your additional comments
Suggestions on the Workshop	
	What are your thoughts on the workshop content? Any suggestions for improvement?
	What are your thoughts on the applied sections of workshop? Any suggestions for improvement?

APPENDIX C

Developed Tool and Games Video Demonstration

In the link below, HoloArch tool’s MR usage video can be seen from HoloLens’ user camera footage:

https://drive.google.com/file/d/14KMIhuBehhwzsnK5tqlxxjMjbNWkBIWK/view?usp=sharing