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# IMMERSIVE DESIGN ENVIRONMENTS FOR PERFORMATIVE ARCHITECTURAL DESIGN: A BIM-BASED APPROACH

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
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BY

ŞAHİN AKIN

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FOR
THE DEGREE OF MASTER OF ARCHITECTURE
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Approval of the thesis:

**IMMERSIVE DESIGN ENVIRONMENTS FOR PERFORMATIVE ARCHITECTURAL DESIGN: A BIM-BASED APPROACH**

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# ABSTRACT

## IMMERSIVE DESIGN ENVIRONMENTS FOR PERFORMATIVE ARCHITECTURAL DESIGN: A BIM-BASED APPROACH

Akın, Şahin
Master of Architecture, Architecture
Supervisor: Assoc. Prof. Dr. İpek Gürsel Dino
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January 2020, 176 pages

In architectural design processes, the use of shared, simulated, and synchronized virtual environments and computational methods becomes widespread. Virtual reality immerses users in a three-dimensional digital environment and has the potential to make them involve actively in the act of design. Daylighting is an essential concept in architectural design, but its assessment and integration to the design process can be complicated. The use of Building Information Modelling (BIM) tools is identified as a critical solution for performance-based architectural design with its integrated simulation tools. In general, both BIM models and performative simulation data are visualized through non-immersive computer displays. In opposition, immersive environments can create an interactive, multi-sensory, first-person view in three-dimensional computer-generated environments, and can increase designers' spatial cognition and perception. This research points out the need for interactive and integrated design tools in immersive environments (IE) to achieve higher performing architectural solutions that support the optimal use of daylighting illumination. In this study, a tool named HoloArch was developed that increases precision and design perception in terms of daylighting performance for

BIM users in IE. HoloArch's user experience studies were conducted in the forms of workshops a user study: DCG Summer School at the University of Lisbon, Immersive and Responsive Environments workshops, and a user study at METU. The feedback was analyzed with both quantitative and qualitative analysis methods. The results show that immersive environments have the potential to augment designers' perception and interaction, to enhance designers' data workflows and to support performative design processes.

Keywords: Immersive Environments, Daylighting, Performative Architecture, Architectural Design, Building Information Modeling

## ÖZ

### PERFORMANS TEMELLİ MİMARİ TASARIM İÇİN ÜÇ BOYUTLU TASARIM ORTAMLARI: BİM TABANLI BİR YAKLAŞIM

Akın, Şahin
Yüksek Lisans, Mimarlık
Tez Yöneticisi: Doç. Dr. İpek Gürsel Dino
Ortak Tez Yöneticisi: Dr. Öğr. Üyesi Elif Sürer

Ocak 2020, 176 sayfa

Tasarım sürecinde, tasarımda paylaşılan, simüle edilmiş ve senkronize sanal ortamların ve hesaplama yöntemlerinin kullanımı yaygınlaşmaktadır. Sanal gerçeklik kullanıcıyı üç boyutlu bir dijital ortama alır ve kullanıcıyı tasarım eylemine aktif olarak dahil etme potansiyeline sahiptir. Mimarlıkta gün ışığı, mimari tasarımda önemli bir kavramdır, ancak değerlendirilmesi ve tasarım sürecine entegrasyonu karmaşık olabilmektedir. Yapı Bilgi Modellemesi (BIM) araçlarının kullanımı, entegre simülasyon araçları ile performansa dayalı mimari tasarım için kritik bir çözüm olarak tanımlanmaktadır. Bununla birlikte, hem BIM modelleri hem de performans simülasyon verileri, çevreleyici olmayan bilgisayar ekranları aracılığıyla görselleştirilmektedir. Buna karşılık, sürükleyici ortamlar etkileşimli, çok duyusal, birinci şahıs görünümlü, üç boyutlu bir ortam oluşturabilmekte ve tasarımcıların mekansal bilişini ve algısını artırabilmektedir. Bu araştırma, gün ışığı aydınlatmasının optimum kullanımını destekleyen daha yüksek performanslı mimari çözümler elde etmek için çevreleyici ortamlarda (IE) etkileşimli ve entegre tasarım araçlarına duyulan ihtiyaca dikkat çekmektedir. Bu çalışmada, IE'deki BIM kullanıcıları için gün ışığı performansı açısından artan kesinlik ve tasarım algısı sağlayan HoloArch adlı bir araç geliştirilmiştir. HoloArch'ın kullanıcı deneyimi çalışmaları iki çalıştayda (Lizbon Üniversitesi'nde DCG Yaz Okulu, ODTÜ'de Çevreleyici ve Duyarlı Ortamlar çalıştayı) ve bir kullanıcı çalışmasında gerçekleştirilmiştir. Elde edilen geri bildirim hem nicel hem de nitel analiz yöntemleriyle analiz edilmiştir. Sonuçlar, çevreleyici ortamların tasarımcının algısını ve etkileşimini artırma, tasarımcıların veri iş akışlarını geliştirme ve yaratıcı tasarım sürecini destekleme potansiyeline sahip olduğunu göstermektedir.

Anahtar Kelimeler: Sanal 3 Boyutlu Ortamlar, Gün Işığı, Performans Temelli Mimari, Mimari Tasarım, Bina Bilgi Modelleme

Born to Blossom, Bloom to Perish…

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This thesis would not be succeeded without the contributions of my dear friend Oğuzcan Ergün who worked very hard to develop and finalize our HoloArch project. I would like to thank him for his tremendous commitment to the project and his easygoing character. He kept working on the development of HoloArch 3.0 for helping me to complete my thesis even after he was graduated. I would also like to thank Ceren Cindioğlu for her help in assisting us during the workshops. I am also grateful for the organization team in Lisbon, especially for Prof. Dr. José Beirão and Rui De Klerk. I would also like to thank Can Köroğlu for hosting me in Lisbon. I would like to thank the participants of our workshops and user study for their suggestions, collaboration, and availability, whose name cannot be cited for ethical reasons.

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## TABLE OF CONTENTS

**LIST OF TABLES**

## LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| **2D** | Two-dimensional |
| **3D** | Three-dimensional |
| **BAP** | Scientific Coordination Unit |
| **BIM** | Building Information Modelling |
| **CAD** | Computer-Aided Design |
| **CAVE** | Cave Automatic Virtual Environment |
| **DCG** | Design Computer Group |
| **HMD** | Head-Mounted Display |
| **IE** | Immersive Environment |
| **LEED** | Leadership in Energy and Environmental Design |
| **METU** | Middle East Technical University |
| **MR** | Mixed Reality |
| **PQ** | Presence Questionnaire |
| **ST.D.** | Standard Deviation |
| **SUS** | System Usability Scale |
| **SWOT** | Strengths, Weaknesses, Opportunities, Threats |
| **TAM** | Technology Acceptance Model |
| **UI** | User Interface |
| **US** | United States of America |
| **UX** | User Experience |
| **VR** | Virtual Reality |
| **YÖK** | Turkish Presidency of the Council of Higher Education |

# CHAPTER 1

# INTRODUCTION

## 1.1 Motivation and Problem Statement

What once appeared to be fictional and futuristic is becoming a reality with the groundbreaking new inventions. The number of new applications, tools, and gadgets introduced and launched is increasing day by day, and catching these technologies' pace is becoming harder. One of the emerging technologies in recent years is the immersive environments (IE). IE offers many potentials for various fields, from education to science, engineering to health. As for architecture, IE is generally used for realistic and dynamic design representations.

Technology in architectural representations came a long way from sketching with pencils to our modern world software programs. The desire for an illusion of being in a non-existent immersive environment has begun with the panoramic paintings in the 18th century and has been extant to our modern world. IE sets forth numerous potentials for architecture in the realistic and dynamic design representation. IE in architecture proposes various components for architects to wander around their models, to explore spatial qualities of their designs, and to control the 3D environment in a perceptive and interactive way.[1] However, depending on the type of the IE (i.e., mixed reality (MR), virtual reality (VR)) user experience may differ. VR offers an entirely cyber milieu that has no connection to physical reality. In VR, users can interact with virtual objects. On the other hand, MR is based on the integration of the

[1] Andries Van Dam et al., "Immersive VR for Scientific Visualization: A Progress Report," *IEEE Computer Graphics and Applications* 20, no. 6 (2000): 26–52, https://doi.org/10.1109/38.888006.

real and virtual worlds together. MR creates a new reality where different objects from different worlds can co-exist and interact simultaneously.[2]

On the other hand, the implementation of IE in the field of architecture is not limited only for visualization of buildings.[3] Currently, architects use this technology as a review and animation tool for creating hyper-realistic visuals or walkthroughs.[4] However, IE can also function as a design medium within where design development can take place.[5] There is an unfulfilled potential for IE in terms of architectural design development. IE is proven to improve design processes by increasing designers' focus on problematic spaces and by allowing them to solve these design problems.[6] IE can offer different levels of detail and scales of perception hence have the potential to empower designers to express, explore and convey design ideas[7] and to envisage the design-related problems before solid models, prototypes, technical drawings, and the final design. As such, IE can enhance decision-making at the early stages of architectural design by supporting design activities regarding identifying, organizing, representing, and interpreting the space.

Building information modeling (BIM) is an object-oriented design medium composed of parametric objects that represent the building elements.[8] BIM consists of smart

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[2] Carlos Flavián, Sergio Ibáñez-Sánchez, and Carlos Orús, "The Impact of Virtual, Augmented and Mixed Reality Technologies on the Customer Experience," *Journal of Business Research* 100 (2019): 547–60, https://doi.org/10.1016/j.jbusres.2018.10.050.
[3] Şahin Akın et al., "Improving Visual Design Perception by an Integrated Mixed Reality Environment for Performative Architecture," in *VIRTUALLY REAL 7th ECAADe Regional International Symposium* (Aalborg, 2019).
[4] David Weidlich et al., "Virtual Reality Approaches for Immersive Design," *CIRP Annals - Manufacturing Technology* 56, no. 1 (2007): 139–42, https://doi.org/10.1016/j.cirp.2007.05.034.
[5] Ibid.
[6] Farzad Pour Rahimian and Rahinah Ibrahim, "Impacts of VR 3D Sketching on Novice Designers' Spatial Cognition in Collaborative Conceptual Architectural Design," *Design Studies* 32, no. 3 (2011): 255–91, https://doi.org/10.1016/j.destud.2010.10.003.
[7] Mark P. Mobach, "Virtual Prototyping to Design Better Corporate Buildings," *Virtual and Physical Prototyping* 5, no. 3 (2010): 163–70, https://doi.org/10.1080/17452759.2010.504085.
[8] Christophe Nicolle and Christophe Cruz, "Semantic Building Information Model and Multimedia for Facility Management," in *Lecture Notes in Business Information Processing*, vol. 75 LNBIP, 2011, 14–29, https://doi.org/10.1007/978-3-642-22810-0_2.

building elements that have self-awareness, which allows the identification of their behaviors.[9] BIM gives professionals opportunities and tools for planning, designing, constructing, analyzing, and managing buildings.[10] Parallel to other contributions of BIM, it is also identified as a critical solution for performance-based architectural design by means of its integrated simulation tools.[11]

Simulation-based design is particularly useful during the early phases of design, which have a maximum impact on the overall performance of a building.[12] Simulation tools can give designers the ability to improve performance across a range of relevant criteria, including daylighting illumination.[13] Spatial daylighting performance, which evaluates the useful daylight introduced to building interiors, is an essential architectural concept. It concerns benefits such as improved health, visual comfort, and energy conservation. According to various studies, lighting systems are responsible for 40-70% of the total electricity consumption in buildings.[14] The efficient and correct use of natural lighting can prevent unnecessary energy consumption and improve sustainability.

On the other hand, typical results of the scientific simulation data, which contain qualitative and quantitative input generally represented as passive, flat, complicated, and in two-dimensional settings, are sometimes found hard to be understood by

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[9] Paola Sanguinetti et al., "General System Architecture for BIM: An Integrated Approach for Design and Analysis," *Advanced Engineering Informatics* 26, no. 2 (2012): 317–33, https://doi.org/10.1016/j.aei.2011.12.001.
[10] Ibid, 3.
[11] Worawan Natephra et al., "Integrating Building Information Modeling and Game Engine for Indoor Lighting Visualization," in *Proceedings of the 16th International Conference on Construction Applications of Virtual Reality,* 2016.
[12] Ibid, 3.
[13] Davide Barbato, Ingegneria Civile, and Paolo Ii, "A Methodological Approach to BIM Design," no. June 2014 (2017).
[14] U.S. Department of Energy, "Buildings Energy Databook," *Energy Efficiency & Renewable Energy Department,* 2012, 286, http://buildingsdatabook.eren.doe.gov/DataBooks.aspx; Thomas G. Dietterich, "Ensemble Methods in Machine Learning," in *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2000, https://doi.org/10.1007/3-540-45014-9_1.

architects and their customers. In addition, most of the simulation results are visualized separately from the 3D context of the model geometry.[15] This kind of problem creates an obstacle in terms of collaboration between clients and architects, even between architects themselves.[16]

The potential of IE in the field of architecture can be expanded with the inclusion of design activities. Architectural design and interacting with architectural models in a virtual environment is possible with the recent developments in technology.[17] In this sense, this thesis looks for solutions that allow designers to interact, edit, and visualize their models through immersive appliances. Rather than offering a new design medium, the thesis tries to find a way to link existing software mediums that serve different demands, together in a continuous bidirectional workflow without data loss. The research does not aim to propose an alternative to the BIM environment, instead focuses on expanding BIM's current effectiveness through the development of a prospective tool in collaboration with game engines' advanced capabilities.

In this thesis, the possible methods for the integration of various concepts such as BIM, interactive architectural design, and performative daylighting simulations into IE were studied, and a new tool named HoloArch was developed as a case study to answer the predetermined research questions of the thesis. HoloArch is intended to offer a more heuristic, intuitional, interactive, and dynamic representation of the scientific simulation data, which can be understandable for everybody through immersive environments.[18] The evaluation of the tool was performed in both national and international workshops and a user study.

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[15] Ibid, 3.
[16] Ibid, 11.
[17] Leif P. Berg and Judy M. Vance, "Industry Use of Virtual Reality in Product Design and Manufacturing: A Survey," *Virtual Reality* 21, no. 1 (2017), https://doi.org/10.1007/s10055-016-0293-9.
[18] Şahin Akın et al., "An Immersive Design Environment for Performance-Based Architectural Design: A BIM-Based Approach," in *ACM International Conference Proceeding Series*, 2018, 306–7, https://doi.org/10.1145/3284869.3284931.

## 1.2 Aims and Objectives

The thesis's primary methodology bases on experimental research[19] by adopting a hybrid method for longitudinal[20] data collection and analysis. The method uses independent variables, and it measures the outcomes or dependent variables with a precise unit of assignment for the treatment of the problem.[21] This research method was adopted throughout the thesis. Due to answer specific research questions of the thesis, a case study tool was developed. The research questions were answered over the proposed tool with the collected data from sample groups in several user studies. Comparisons between IE types with different participant groups along with different versions of the developed tool were tested, simulated, digitized; then the outputs were evaluated. The proposed tool's user experience studies were conducted in both national, international workshops, and a user study. The main aims and objectives of this thesis are;

- A literature review on immersive environments in performative architecture and building information modeling and the connections between these concepts should be presented.
- Commonly used commercial architectural performance-based assessment and immersive tools for architecture should be examined, and their potentials and limitations should be revealed.
- According to the found potentials and limitations in the literature, an integrated tool that addresses the current problems should be developed.

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[19] Kerry Tanner, "Experimental Research," in *Research Methods: Information, Systems, and Contexts: Second Edition*, 2018, https://doi.org/10.1016/B978-0-08-102220-7.00014-5.
[20] Edward Joseph Caruana et al., "Longitudinal Studies," *Journal of Thoracic Disease* 7, no. 11 (November 2015): E537–40, https://doi.org/10.3978/j.issn.2072-1439.2015.10.63.
[21] Klaus Hinkelmann, *Design and Analysis of Experiments*, *Design and Analysis of Experiments*, vol. 3, 2012, https://doi.org/10.1002/9781118147634.

- The proposed tool should be compatible with the current immersive technologies to be able to widen its influence area and affordances for the field of architecture.
- After the development of the tool is completed, its validation and evaluation should be performed with user studies to reveal its achievements and contributions to the field of architecture.
- The tool's future potentials and current limitations should be addressed in order to be an example for the other researchers interested in similar integrated environments for architecture.

## 1.3 Research Questions

Based on the research gap introduced in the introduction section, the main research question along with its sub-questions emerged as;

**Main thesis questions:** To which extent immersive design environments support performative architectural design processes, especially daylighting? Could it be possible to integrate various concepts in a single immersive environment where performative design actions could be performed? May these integrated environments guide its users to achieve efficient design solutions and to understand the importance of performative design?

**Sub-Questions:** What are the current implementation of IE to the field of architecture and performative design in the literature? Is it possible to develop a tool to answer the main questions of this thesis? What are the technologies needed to be integrated, and what are the requirements addressed for the tool? Could it be possible to construct a reversible workflow between IE and BIM platforms for the proposed tool and what kind of benefits could this approach provide designers? What kind of benefits does the proposed tool which combines BIM, performative architectural design, and IE provide for architects? Which data collection, analysis, and evaluation methods should be adopted to understand the strengths and weaknesses of the proposed tool? Which immersive technology type is more suitable for the proposed tool at the current conditions in technology? How could the model interaction and perception differ between immersive technologies for the proposed tool?

## 1.4 Contributions

By answering the research questions, this thesis contributes to the field of architecture as follows;

- The significant problems in the literature for the integration of BIM, performative simulations, and immersive environments were detected.
- An integrated tool named HoloArch for mixed and virtual reality environments was developed as a case study to be a possible solution to the detected problems in the existing literature.
- HoloArch was developed in collaboration with the Middle East Technical University's (METU) Department of Architecture and Multimedia Informatics Program by Assoc. Prof. Dr. İpek Gürsel Dino, Assist. Prof. Dr. Elif Sürer and M.Sc. Oğuzcan Ergün. The thesis work was a part of BAP (Scientific Coordination Unit) projects supported by METU YÖP-704-2018-2827 and METU GAP-201-2018-2823 grants.
- An uninterrupted bi-directional workflow that provides data transfer without any significant data loss between game engines and smart BIM platforms was found and tested for HoloArch.
- HoloArch was examined and evaluated in the workshops and a user study to reveal the potentials, problems, and limitations of the integration of different concepts to immersive environments.
- For HoloArch, a comparative study for finding the most appropriate IE type was conducted.
- In the framework of this thesis, an international workshop was held in Lisbon as a part of the Design Computation SummerSchool 2018,

organized by the Design Computation Group of the Faculty of Architecture, University of Lisbon, under the title "Immersive and Responsive: Performative Architectural Design in Mixed Reality". Additionally, a national workshop was organized by the METU Department of Architecture and the METU Multimedia Informatics Program. In these workshops, many architecture students with different backgrounds were taught about different topics, including BIM, performative simulations, and IE. The participants had the chance to understand the potentials of the IE in architectural practices and to gain insights about state of the art immersive technologies.

This research allowed the following papers to be published and presented at international conferences to reach a broad audience:

- Akin, Sahin, Oğuzcan Ergün, Ipek Gursel Dino, and Elif Surer. "Improving Visual Design Perception by an Integrated Mixed Reality Environment for Performative Architecture." In VIRTUALLY REAL 7th ECAADe Regional International Symposium. Aalborg, 2019.
- Akin, Sahin, Oğuzcan Ergün, Elif Surer, and Ipek Gursel Dino. "An Immersive Design Environment for Performance-Based Architectural Design: A BIM-Based Approach." In ACM International Conference Proceeding Series, 306–7, 2018.
- Ergün, Oğuzcan, Sahin Akin, Ipek Gursel Dino, and Elif Surer. "Architectural Design in Virtual Reality and Mixed Reality Environments: A Comparative Analysis." In 26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019 - Proceedings, 914–15, 2019.

## 1.5 Chapter Overview

The thesis consists of six main chapters, including the current chapter. The current chapter presents an overview of the involved topics along with this thesis' research questions, motivation, and its contribution to the field of architecture. The upcoming chapters' contents can be briefly explained as follows,

**Chapter 2:** Literature Review, this chapter consists of a brief literature review on building information modeling, performative architecture, and their relationship with immersive platforms. In addition to academic research work conducted in the involved topics, this chapter also gives comprehensive coverage on some of the most recent and relevant software examples from the industry as well. The chapter also points out the missing parts of the literature and industry by drawing attention to the need for an integration tool.

**Chapter 3:** An Integrated Environment for Immersive Environments: HoloArch, the chapter explains the central methodology of the thesis, which is the development of a case study tool to answer the research questions. The chapter covers the development process of the tool named HoloArch that aims to bridge the gap between the involved topics and to fill the void in the literature. HoloArch's technical details, features, its implementation to IE, workflow, components, requirements, and its versions are expounded in detail.

**Chapter 4:** The Workshops, both national and international workshops, were organized as a part of the evaluation and validation of the HoloArch project. This chapter reports the preparation stages of the user experience workshops by explaining their participants, adapted technologies, contents, duration, data collection methods, and it presents the outputs of the workshops by discussing their findings.

**Chapter 5:** The User Study, this chapter reports the user study conducted with the most advanced version of HoloArch 3.0. The chapter expounds on the experimental user study setup, the participants, the used technologies, and the adapted qualitative and quantitative data collection and analysis methods of the user study. Also, it presents and discusses the findings from the obtained feedback in a structured way.

**Chapter 6:** Conclusion, the last chapter of the thesis, runs back over the findings of the conducted workshops and the user study once again in a summative way. In the chapter, the research questions of the thesis are answered in light of the findings. Also, the conclusion touches on the future opportunities and possibilities of similar tools to HoloArch.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Performative Architecture

### 2.1.1 Performance Notion in Architecture and Performative Turn

The performance is one of the prominent discourse in the field of architecture. Beginning from the mid-18th century after the rapid advancements in science, especially in biology, enabled to arise of the performative approach in architecture. This notion's maturation process has been accelerated with the emergence of notions such as *Umwelt, environment,* and *milieu* in the literature.[22] The performative turn among the various disciplines in the 20th century also had a significant impact on the emergence of performative thinking in architecture.[23] The turn cannot be confined only in architecture and according to Smitheram:

> "turn" loosely refers to the different apprehensions of the performative, as a means to theorize, make, understand, or act in the world."[24]

The main reason for the emergence of the performative turn can be interpreted as getting away from traditional ways of knowing and perpetual traditions.[25] Moreover, according to Schilling:

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[22] Michael Hensel, *Performance-Oriented Architecture: Rethinking Architectural Design and the Built Environment*, 2013, https://doi.org/10.1002/9781118640630.
[23] Cem Ataman, "Performative Design Thinking In Architectural Practice," 2018.
[24] Jan Smitheram, "Spatial Performativity/Spatial Performance," *Architectural Theory Review* 16, no. 1 (April 2011): 55–69, https://doi.org/10.1080/13264826.2011.560387.
[25] Catherine Nash, "Performativity in Practice: Some Recent Work in Cultural Geography," *Progress in Human Geography* 24, no. 4 (2000): 653–64, https://doi.org/10.1191/030913200701540654.

> "performative process breaks the boundary between traditionally divided units and enables the communication between object and spectator and the dissolution of spatial boundaries which originally separated both of them."[26]

After the turn, the notion of performance started to be embraced and resonated more by the architecture world with the help of semiotics trend in architecture, which argues architecture as a language and interests the meaning-making with the essence of the words. The notion of performance became apparent in architecture after the involvement of the turn.

According to Michael Hensel, performance has been understood and applied differently by the various groups of designers. He grouped different approaches in five parts. The first approach is based on radical eclecticism where form and function separated from each other and examined independently, and each element and space have no obligations to satisfy each other.[27] Therefore the performance was addressed separately from form and function. The second and third approach was on the ongoing debate of relation between form and function. In these approaches, formal properties were seen as related to the aesthetics and artistic qualities of the architecture, contrarily functional properties were admitted as qualities that deal with engineering and science.[28] Performance notions were grasped formally and functionally but separately. As understood that, in these three approaches, the fully integrated performance understanding in architecture cannot be mentioned. On the other hand, the fourth approach is focused on the event notion, which can be seen in the writings of Tschumi. He argued that architecture presents an extraordinary relationship between events and space.[29]

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[26] Asterios Agkathidis et al., *Performative Geometries Transforming Textile Techniques*, 2010.
[27] Ibid, 22.
[28] Ibid.
[29] Bernard, Tschumi, *Introduction : Notes Towards A Theory Of Architectural Disjunction*, *In Architecture And Urbanism*, no.216, pp13-15, 1988.

Finally, the fifth approach focusses on building performance, the expected and unforeseen activities that occur in the building. Ideas of David Leatherbarrow, Branko Kolarevic, and Ali Malkawi about the notion of performance can be given as examples in this approach.[30] Leatherbarrow states that building is a uniform complex that consisted of aesthetical and technical properties but it could be evaluated through its relationship with its environment, actions and only by its performances.[31] Leatherbarrow also says that the building's performance could never be genuinely rationalized and known because it is hard to predict how the building interacts with the environment in various situations, the building is dynamic and active which always in a challenge with its internal (occupants) and external (weather) parameters.[32] Harmoniously, Malkawi, and Kolarevic added that:

> "emphasis on building performance … is influencing building design, its processes, and practices, by blurring the distinction between geometry and analysis, appearance and performance." [33]

A more integrated notion of performance can be found in the fourth and fifth approaches rather than an eclectic way of thinking the performance. According to Bechthold, the notion of performance needs to be part of every project as a social duty for society and environment while global warming and the scarcity of the natural sources are increasing each day.[34] It does not have to be an architectural movement similar to other *"–isms"* but should be the mandatory element of design thinking.

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[30] Branko Kolarevic, Ali Malkawi, and Ali Malkawi, "Architecture's Unscripted Performance (Leatherbarrow)," July 8, 2005, 11–26, https://doi.org/10.4324/9780203017821-2.
[31] Ibid.
[32] Ibid.
[33] Dana Buntrock, *Architecture in the Digital Age: Design and Manufacturing and Performative Architecture: Beyond Instrumentality - Edited by Branko Kolarevic, Branko Kolarevic and Ali Malkawi, Journal of Architectural Education*, vol. 60, 2006, https://doi.org/10.1111/j.1531-314x.2006.00068_1.x.
[34] Yasha J. Grobman and Eran Neuman, "Performalism: Form and Performance in Digital Architecture," in *Performalism: Form and Performance in Digital Architecture*, 2013, 1–210, https://doi.org/10.4324/9780203720981.

### 2.1.2 Performance-Based Design in Architecture

Performance-based design as a general description is evaluation and documentation of the building under specific environmental threads; it also includes that how the building reacts and bears to potential external hazards and sustains its everyday operation without giving any sacrifices. The International Code Council describes the performance-based design as:

> "An engineering approach to design elements of a building based on agreed-upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against the design goals and objectives using accepted engineering tools, methodologies, and performance criteria." [35]

It can be inferred that building performance and the comfort level of its inhabitants are directly interrelated. It also gives insights about how well the building is. The performance-based designs have become more critical in today's world's challenges any other time before with the extreme differences in environmental conditions, global warming, and the diminishing of natural sources. The evaluation criteria of buildings now are not measured by how it looks; instead, it is more related to how many needs of its inhabitants, owners, and investors addressed. The main goal of the performance-based design is based on the creation of the structures that socially, economically and environmentally serve to the society in the most profitable way. According to William Clark, the buildings are the core of sustainability science and located where the humans and the environment intersect each other. In this regard, he defined buildings as:

> "fundamental properties of the complex, adaptive human-environment systems."[36]

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[35] *2015 ICCP C ® International Code Council Performance Code ® For Buildings And Facilities Code Alert!*, 2014, www.iccsafe.org/2015alert.

[36] William C. Clark, "Sustainability Science: A Room of Its Own," ed. William C Clark, *Proceedings of the National Academy of Sciences of the United States of America* 104, no. 6 (2007): 1737–38, https://doi.org/10.1073/pnas.0611291104.

Performance-oriented architecture is looking through the past where thousands of years of knowledge have been accumulated through the experiences and experiments of former generations and combining these principles with today's laboratory and simulation observations to understand nonlinear behavior of the elements and components.[37] Performance-based simulations help designers to design better-performing buildings.[38] In this regard, the integration of performative thinking to our architectural design processes should be an essential element rather than an optional decision for designers.

### 2.1.3 Performative Architecture and IE

There are a lot of performance-based simulation tools widely used by professionals. However, only a limited number of studies focus on the integration with IE. The visualization of architectural simulation results in IE is a rather unaddressed field in the literature. However, the inevitable boom in immersive technologies enabled that performative simulation found a place in the field. For instance, Natephra et al. presented a VR tool named BLDF which allows users to export their BIM models to VR.[39] Users can simulate artificial and natural lighting on the platform and decide which type of luminaires they can use. However, the system was only for conventional VR, which is independent of the physical world. In addition, Alcini et al. studied the daylighting effects for eight floors of the underground city by using daylighting analysis results which were conducted by using Dialux.[40] However, the simulation results were used as imbricated 2D images in a 3D environment. Araujo

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[37] Chris Luebkeman, "Performance-Based Design," in *Architecture in the Digital Age: Design and Manufacturing*, 2004.
[38] Rivka Oxman, "Performance-Based Design: Current Practices and Research Issues," *International Journal of Architectural Computing*, 2008, https://doi.org/10.1260/147807708784640090.
[39] Ibid, 11.
[40] Cristiano Merli Alcini, Samuele Schiavoni, and Francesco Asdrubali, "Simulation of Daylighting Conditions in a Virtual Underground City," *Journal of Daylighting*, 2015, https://doi.org/10.15627/jd.2015.1.

et al. presented a lighting simulation tool in VR for particular events such as concerts and nightclubs.[41] The paper focused more on the lighting design of the artificial fixtures in big ceremonies. On the other hand, Fukuda et al. presented an integrated design tool by coupling concepts such as augmented, virtual reality, BIM and computational fluid dynamics (CFD).[42] The tool visualizes CFD simulation results in an integrated way inside the building geometry. Bahar et al. used MR based system for visualization of thermal building simulations.[43] The simulation results have been tested in many waysdo such as colored cubes and layered particles, to find which type of graphical visualization is more informative. However, similar to Fukuda et al. and Araujo's researches, they did not include daylighting simulations into their studies.

Apart from academic studies, a commercial tool called Enscape[44] allows real-time rendering in VR. It allows design editing through a computer. The changes made in the BIM tools are simultaneously synchronized with the VR gadget. However, VR user needs other people who perform design editing actions. In addition, Enscape visualizes artificial and natural illumination values in LUX as a view option. However, the tool is not available for MR environments and the visualized lux values give only limited visual feedback.

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[41] João Araujo, JCTR 2014, Virtual Reality for Lighting Simulation in Events, Master's Thesis, Instituto Superior Tecnico, Lisbon, Portugal.
[42] K Yokoi et al., "Integrating BIM, CFD and AR for Thermal Assessment of Indoor Greenery," *22nd International Conference on Computer-Aided Architectural Design Research in Asia: Protocols, Flows and Glitches, CAADRIA 2017*, 2017, 85–94, https://www.scopus.com/inward/record.uri?eid=2-s2.0-85021733431&partnerID=40&md5=b77e55a9b55658201cb78dbaa21ed572.
[43] Yudi Nugraha Bahar et al., "Integration of Thermal Building Simulation and VR Techniques for Sustainable Building Projects Science Arts & Métiers ( SAM )," no. March (2015).
[44] "Enscape™ - Real-Time Rendering for Revit, SketchUp, Rhino & ArchiCad," accessed January 17, 2020, https://enscape3d.com/.

## 2.2 Building Information Modelling (BIM)

The design of a project and its realization are complex tasks that require a vast amount of information and collaboration from various different disciplines. It is extensively known that construction management processes go through the lack of efficient practices in almost every phase of the buildings, from sketching to its realization. Every mistake has been made turns stakeholders back to as a waste of material, time and money.[45] Even though computer-aided design software programs have been engaged with the architects of our time, the new technologies brought new problems in terms of communication between architects and other professions.

The construction and design phases where different design platforms involved often face conflicts and mistakes throughout the realization process of buildings.[46] This situation far to sustain errorless workflow in the project because building-related data often cannot be transferred appropriately between different mediums. Several studies show that CAD-based platforms provide better flexibility compared to 2D conventional drawings for data preservation and management.[47] However, with the overgrowing construction sector, CAD tools may fall in short to respond to the needs of designers. The problem here does not arise from the CAD tools modeling limitations or visualization of the model rather bases on the data storage and query capabilities of the environment. The more projects expanded, the more difficult data management becomes. In this regard, CAD platforms are limited to contain all of the building's data and do not offer their element's relationship with each other. These

[45] Zhen Chen, "Grand Challenges in Construction Management," *Frontiers in Built Environment* 5 (2019): 31, https://doi.org/10.3389/fbuil.2019.00031.
[46] Tarek Hegazy, Essam Zaneldin, and Donald Grierson, "Improving Design Coordination for Building Projects. I: Information Model," *Journal of Construction Engineering and Management*, 2001, https://doi.org/10.1061/(ASCE)0733-9364(2001)127:4(322).
[47] Ireneusz Czmoch and Adam Pękala, "Traditional Design versus BIM Based Design," in *Procedia Engineering*, vol. 91 (Elsevier Ltd, 2014), 210–15, https://doi.org/10.1016/j.proeng.2014.12.048.

limitations in the CAD environment pave the way for the emergence of a different modeling concept called building information modeling (BIM).

According to ISO, the Building Information Model is described as:

> "shared digital representation of physical and functional characteristics of any built object… which forms a reliable basis for decisions."[48]

On the other hand, according to the Natural Institute of Building Sciences outlines BIM as:

> "A Building Information Model, or BIM utilizes cutting edge digital technology to establish a computable representation of all the physical and functional characteristics of a facility and its related project/life-cycle information, and is intended to be a repository of information for the facility owner/operator to use and maintain throughout the life-cycle of a facility."[49]

For a more straight forward definition, BIM consists of smart building elements that ''know'' what they are, how they behave, and store all the desired information about the elements.[50] BIM allows storing geometric or non-geometric parameters, attributions with operational, semantic, functional, or topological data.[51] These stored data can be used whenever it is required, which allows the reuse of information.[52] This information can be tracked, managed and changed easier compared to CAD tools. BIM is not only a single software that all the data are gathered in one place; instead, it is the sum of total information generated throughout

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48 ISO Standard. ISO 29481-1:2010(E): Building Information modeling - Information delivery manual - Part 1: Methodology and format (2010).

49 National Building Information Modeling Standard (NBIMS), National Building Information Modeling Standard Version 1.0 (2007).

50 Xiangyu Wang, "BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors," *Construction Economics and Building* 12, no. 3 (2014): 101–2, https://doi.org/10.5130/ajceb.v12i3.2749.

51 Bilal Succar, "Building Information Modelling Framework: A Research and Delivery Foundation for Industry Stakeholders," *Automation in Construction* 18, no. 3 (2009): 357–75, https://doi.org/10.1016/j.autcon.2008.10.003.

52 Yusuf Arayici et al., "Technology Adoption in the BIM Implementation for Lean Architectural Practice," *Automation in Construction* 20, no. 2 (2010): 189–95, https://doi.org/10.1016/j.autcon.2010.09.016.

the building design. BIM is an object-oriented design medium that is composed of parametric objects that represent the building elements.[53] BIM offers parametric totality where all the elements are interrelated with each other by predefined conditions and constraints. This integrity sustains even when the model is being edited.[54]

### 2.2.1 Building Information Modelling and IE

The transitional change towards smart BIM platforms in the industry facilitated the extension of its capabilities to address the needs of architects over rapidly developing technologies. One of the implemented technologies from recent years is the interactive IE. There is a growing demand for the integration of BIM and IE. This research field was addressed previously in terms of design review[55], design feedback[56], education[57], and construction[58].

The integration of IE in architectural visualization is not new, and many previous studies were conducted with different types of IE with various technologies. Clevenger et al. developed a BIM-supported tool to understand the roles of 3D

[53] Ibid, 8.
[54] Farzad Khosrowshahi, "Building Information Modelling (BIM) a Paradigm Shift in Construction," in *Building Information Modelling, Building Performance, Design and Smart Construction* (Springer International Publishing, 2017), 47–64, https://doi.org/10.1007/978-3-319-50346-2_4.
[55] Stefan Krakhofer et al., "Augmented Reality Design Decision Support Engine for the Early Building Design Stage," *Emerging Experience in Past, Present and Future of Digital Architecture, Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2015)* , 2015, 231–40.
[56] Arsalan Heydarian et al., "Immersive Virtual Environments: Experiments on Impacting Design and Human Building Interaction," *Rethinking Comprehensive Design: Speculative Counterculture - Proceedings of the 19th International Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA 2014*, 2014, 729–38.
[57] Nuria Martí et al., "Visualization Methods in Architecture Education Using 3D Virtual Models and Augmented Reality in Mobile and Social Networks," *Procedia - Social and Behavioral Sciences* 93 (2013): 1337–43, https://doi.org/10.1016/j.sbspro.2013.10.040.
[58] Alcinia Zita Sampaio, "Enhancing BIM Methodology with VR Technology," in *State of the Art Virtual Reality and Augmented Reality Knowhow*, 2018, https://doi.org/10.5772/intechopen.74070.

visualization in safety training in construction.[59] Williams et al. developed a tool called BIM2AR for mobile MR environments in order to examine facility management in healthcare facilities.[60] Meza et al. focused on how to use BIM information for augmented reality (AR).[61] They implemented a BIM-based AR system that consists of four activities: creating BIM, creating a schedule, creating an AR model, and using an AR model on site.

The implementation of IE and BIM models created a new field in the swiftly growing software industry. Apart from academic research work, there are a number of software tools that address different solutions for the AEC (architecture, engineering, construction) community. An MR tool called BIM-Holoview[62] visualizes 3D BIM models accurately on-site as an overlay layer of the physical building. Holoview enables the visualization of hidden elements of the building including mechanical and structural elements. However, the system acts only as a visualization tool for building elements. Another tool named Autodesk Revit Live[63], provides interactive visualization of BIM models. Revit Live enables users to see the impacts of lighting and shadows throughout the year in real-time, but it does not allow design editing, and its supported environment is only for VR gadgets. On the other hand, a visualization tool named Enscape  allows real-time rendering in VR similar to Revit Live, but it only allows simultaneous design editing through a computer. The changes made in the BIM tools are simultaneously synchronized with the VR gadget.

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[59] Caroline Clevenger and Scott Glick, "Advances in Engineering Education Interactive BIM-Enabled Safety Training Piloted in Construction Education AND," *Advances in Engineering Education* 4 (2015): 1–14.
[60] Graceline Williams et al., "BIM2MAR: An Efficient BIM Translation to Mobile Augmented Reality Applications," *Journal of Management in Engineering* 31, no. 1 (2014): A4014009, https://doi.org/10.1061/(asce)me.1943-5479.0000315.
[61] Sebastjan Meža, Žiga Turk, and Matevž Dolenc, "Component Based Engineering of a Mobile BIM-Based Augmented Reality System," *Automation in Construction* 42 (2014): 1–12, https://doi.org/10.1016/j.autcon.2014.02.011.
[62] "BIM Holoview," 2018, http://www.bimholoview.com/.
[63] Autodesk, "Revit Live | Immersive Architectural Visualization," 2019, https://www.autodesk.com/products/revit-live/overview.

However, VR user needs other people who sit and control design editing actions. This approach is useful for client-designer collaboration but hinders designing experience that can be realized inside IE. There are a number of other commercial immersive tools for the BIM users exist. However, none of them offers an integrated environment for gathering BIM, IE, and performative architectural design together.

# CHAPTER 3

# AN INTEGRATED ENVIRONMENT FOR IE: HOLOARCH

According to the literature review and the main problem statements of this thesis, it can be inferred that there is a need for an integrated tool focusing on expanding capabilities of BIM, integrating daylighting simulations into design processes, and testing architectural design possibilities in immersive environments. As a methodology of the thesis, a responsive and interactive tool was aimed to be developed in order to be a solution to the existing problems in the mentioned specific fields of architecture. In this manner, a tool named HoloArch was developed by Assoc. Prof. Dr. İpek Gürsel Dino, Assist. Prof. Dr. Elif Sürer and M.Sc. Oğuzcan Ergün as a part of a fully-funded BAP (Scientific Coordination Unit) project in collaboration with the METU Department of Architecture and Multimedia Informatics Program. Assoc. Prof. Dr. İpek Gürsel Dino and Assist. Prof. Dr. Elif Sürer contributed to the project mainly in terms of project administration, supervision, funding acquisition, and conceptualization. The whole team contributed to the project in the development of design methodology, the organization of the user studies with participants, the writing of the publications, and project reports. M.Sc. Oğuzcan Ergün contributed to the project particularly in the programming, the implementation of the computer codes and supporting algorithms, and testing of existing code components. Oğuzcan and I were both responsible for the investigation of tool implementation, software development, and UI design. Finally, I contributed to the project in the identification of the tool requirements, BIM data workflows, giving workshop lectures to the participants, planning of the design tasks for participants, data collection, visualization, analysis, and validation.

HoloArch's name comes from the combination of "*Holo*" and "*Arch*", which are abbreviations representing of hologram and architecture. HoloArch was designed as a case study to be able to answer this thesis' research questions.

## 3.1 Initial Theme Definition and Selection of Primary Components

HoloArch was designed to overcome the lacking and unsatisfactory topics in the current literature by focusing on the selected themes. By focusing on the relevant subjects and narrowing down the broad range of topics in the system, the development of the application was facilitated more concentratedly. For instance, rather than determining the central theme as architectural design, the performative architectural daylighting design was targeted to ease the development of the intrigued tool. HoloArch was developed as both a mixed and VR tool for designers to work in immersive environments. HoloArch's logo can be seen in *Figure 3.1*, along with alternative logo designs.


*Figure 3.1*. Finding a name and a logo for the proposed tool

### 3.1.1 The Selection of Performative Analysis Type

The primary performance analysis type was selected as daylighting simulations because of its importance and applicable nature to the framework of this thesis. The reasons of why daylighting was adopted as a primary performative tool for HoloArch can be explained by:

- The assessment of daylighting is multi-objective. It is based on four pillars, including comfort, energy, health, and perception.[64] Except for the health pillar, the other pillars of daylighting were found fully compatible with immersive environments and HoloArch's aims, objectives, claims foreseen to be proved. Three of the pillars have an impact both directly and indirectly to the built environment and its users.
- The daylighting design of buildings can be realized, be manipulated, and be controlled by visible interventions to the architecture.[65] For instance, the replacement of a window, location of shading elements, design of the landscape, and selection of building materials have direct effects on the architecture of buildings. In this regard, the performative daylighting design actions of HoloArch might be able to present interactive and visible feedback to its users by allowing editing architectural elements. These actions could be facilitated as easy as placing a tree outside of buildings or placing a shading device in front of openings.
- Daylighting simulations can be reduced to a representative day. Compared to convoluted annual energy simulations, daylighting simulations can be represented by selecting a specific time interval (i.e., equinoxes and

[64] Giorgia Chinazzo, Jan Wienold, and Marilyne Andersen, "Daylight Affects Human Thermal Perception," *Scientific Reports* 9, no. 1 (2019), https://doi.org/10.1038/s41598-019-48963-y.
[65] Kevin van den Wymelenberg and Christopher Meek, "Simulation-Based Daylighting Design Education and Technical Support," *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, 2011, http://www.commercialwindows.org/facade.php].

solstices), and this allows daylighting simulations to be performed in a shorter time.[66]

- Design with daylighting is a visual act. Daylighting performance simulations can be represented visually[67] and are directly related to the spaces and architectural elements of buildings. For instance, the dimensions of an opening have a dramatic impact on the daylighting simulations of a specified room. Compared to energy simulations' graphical outputs, daylighting analyses can be represented more tangibly and in an integrated way with the building.

The selection of daylighting simulations shaped and contributed the framework of HoloArch to be a more versatile tool where various performative design actions can be facilitated visually, interactively, and these actions results can give fast and visual feedback to the users.

### 3.1.2 The Selection of BIM Environment

The advantages of BIM over conventional CAD platforms were identified previously in the earlier chapters. For the mentioned capabilities of BIM environments, HoloArch was established on a BIM-based approach from the beginning of the project till the end. However, there are numerous BIM software tools, and a selection between them was necessary for the upcoming developments of HoloArch. The most widely used BIM platforms in the industry can be specified as Autodesk Revit,

[66] James Sullivan and Michael Donn, "Some Simple Methods for Reducing Daylight Simulation Time," *Architectural Science Review* 61, no. 4 (July 4, 2018): 234–45, https://doi.org/10.1080/00038628.2018.1464896.

[67] Christoph F. Reinhart and Jan Wienold, "The Daylighting Dashboard - A Simulation-Based Design Analysis for Daylit Spaces," *Building and Environment*, vol. 46, 2011, https://doi.org/10.1016/j.buildenv.2010.08.001.

ArchiCad, Bentley Architecture, Tekla BIMsight.[68] For the HoloArch project, Autodesk Revit environment was selected, and the whole design process was established on the Revit platform because of the following specifications of the software tool;

- Autodesk Revit is a common and preferred software platform among designers. According to the National BIM Report 2019, 46% of the total BIM professionals preferred Autodesk Revit among the other BIM tools.[69] Apart from that, the developers had background knowledge in Autodesk Revit, and this was important to understand how the system can actually perform when it is integrated with HoloArch. For the upcoming user studies for HoloArch's evaluation, finding people who can use Autodesk Revit properly, was easier compared with finding Bentley Architecture or ArchiCAD users.
- Autodesk Revit has enriched data workflow capabilities. By using the broadly accepted tool in the field, data related integration issues can be solved more smoothly and quickly.[70] As stated in Ergün's thesis, Autodesk Revit allows to export and import a wide range of data file formats including "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))."[71] This flexible platform also can provide HoloArch appealed by larger user groups.

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[68] NBS, "National BIM Report 2019," *National BIM Report 2019 :The Definitive Industry Update*, 2019, https://doi.org/10.1017/CBO9781107415324.004.
[69] Ibid.
[70] Nicolas Alexandros Papadopoulos Et Al., "Evaluation of Integration Between a Bim Platform and a Tool for Structural Analysis," *Systems & Management* 12 (2017): 108–16, Https://Doi.Org/10.20985/1980-5160.2017.V12n1.1203.
[71] Oğuzcan Ergün, "Developing Building Information Modelling Based Virtual Reality And Mixed Reality Environments For Architectural Design And Improving User Interactions With Serious Games" Middle East Technical University, (2019).

- Autodesk Revit has various integrated performative tools. Revit is integrated with many performance-based assessment tools that allow conducting mechanical, structural, energy, comfort, and daylighting simulations by using user-created BIM models as a base.[72] Rather than using a standalone BEM (Building Energy Modeling) platforms such as DesignBuilder or Sefaira, Revit has its own built-in assessment tools allowing smooth workflow without any data loss. In addition, Revit was chosen to keep the framework as simple as possible and to prevent involving other additional tools that might lead to a chaotic workflow for HoloArch.

For the abovementioned reasons, the Autodesk Revit environment was selected as the base BIM environment of HoloArch for its integrated performative assessment tools, its extensive audience coverage, and its data workflow capabilities.

### 3.1.3 The Selection of Immersive Appliances

HoloArch was designed to serve both virtual and mixed reality environments. Since these distinct environments offer unique experiences to their users, both of the systems were added to the development agenda of HoloArch. As of 2018, there were several technologies in the customer market for providing virtual and mixed reality experiences. While the prominent mixed reality appliances could be exemplified as Microsoft HoloLens and Meta2, the most popular HMDs for VR were HTC Vive and Oculus Rift. Hence, the HoloArch project was initiated in 2018; the appliance selections for HoloArch were chosen according to the available technologies of the period. In conclusion, Microsoft HoloLens for mixed reality and HTC Vive for VR were selected as the main immersive appliances.

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[72] Zahra Pezeshki and Syed Ali Soleimani Ivari, “Applications of BIM: A Brief Review and Future Outline,” in *Archives of Computational Methods in Engineering*, vol. 25, 2018, 273–312, https://doi.org/10.1007/s11831-016-9204-1.

- Microsoft HoloLens:

  Microsoft HoloLens is basically a head-mounted untethered computer that has a holographic display. The appliance was one of its kind and the first holographic computer in the world.[73] HoloLens offers new ways to empower users' immersive experiences by providing 3D holograms that are anchored to physical reality. The real innovation with this headset is that it combines several advanced technologies into a single, autonomous, and portable device.[74] HoloLens brings different sophisticated technologies together, such as see-through projection lenses, voice recognition, gesture tracking system, scanners, binaural spatial audio, sensors (*Figure 3.2*). HoloLens device can extend interaction with 3D models beyond the confinements of 2D conventional displays. The appliance is controlled by hand gestures rather than any control devices. Hence Microsoft HoloLens was a breakthrough device for MR; it was selected as an MR experience provider for the HoloArch project.

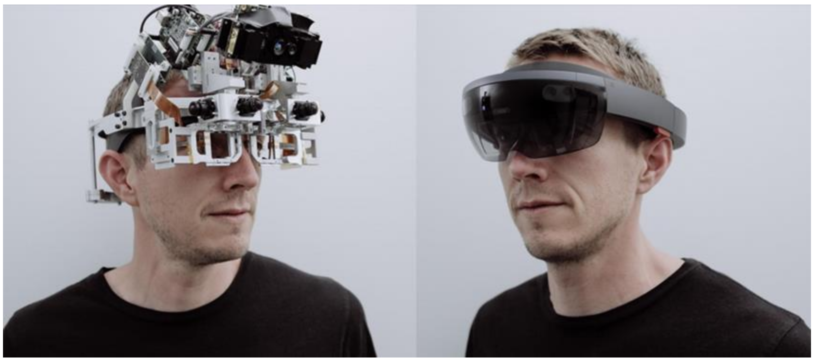

*Figure 3.2.* Microsoft HoloLens Gathers Different Technologies Together[75]

[73] Yang Liu et al., "Technical Evaluation of HoloLens for Multimedia: A First Look," *IEEE Multimedia* 25, no. 4 (2018): 8–18, https://doi.org/10.1109/MMUL.2018.2873473.
[74] Adrien Coppens, "Merging Real and Virtual Worlds: An Analysis of the State of the Art and Practical Evaluation of Microsoft Hololens" (2017), http://arxiv.org/abs/1706.08096.
[75] "Microsoft Hololens - by Microsoft Device Design Team / Core77 Design Awards," accessed February 6, 2020, https://designawards.core77.com/Consumer-Product/51416/Microsoft-Hololens.

- HTC Vive:

  HTC Vive is a virtual reality goggle. HTC Vive offers a total resolution of 2160 x 1200 pixels. This means a resolution of 1080 x 1200 pixels per eye.[76] The HTC glasses also offer a refresh rate of 90Hz that can prevent the occurrence of motion-sickness.[77] The glasses act as a display device rather than a standalone computer. It means that for VR experiences, a computer is required. It has two controllers and two base stations to understand user actions *(Figure 3.3*). The base stations contain a power cable, but allow data transfer over the wireless network, which is an advantage in order to avoid cable clutter. HTC Vive base stations can detect user movements within 15 square meters.[78] Since HTC Vive was within reach and widely used technology in the country, it was adopted for the project.


*Figure 3.3.* HTC Vive components[79]

[76] HTC, "VIVE Discovery Virtual Reality Beyond Imagination," *Vive Website*, 2016.
[77] Adrián Borrego et al., "Comparison of Oculus Rift and HTC Vive: Feasibility for Virtual Reality-Based Exploration, Navigation, Exergaming, and Rehabilitation," *Games for Health Journal* 7, no. 3 (2018): 151–56, https://doi.org/10.1089/g4h.2017.0114.
[78] Miguel Borges et al., "HTC Vive: Analysis and Accuracy Improvement," in *IEEE International Conference on Intelligent Robots and Systems*, 2018, 2610–15, https://doi.org/10.1109/IROS.2018.8593707.
[79] Ibid, 76.

### 3.1.4 The Selection of Game Environment

As a conventional representation method, architects generally use 2D pre-rendered images to visualize their designs. On the other hand, real-time and life-like renderings, animations, or walkthrough apps for designers can be realized with the tremendous aid of game development platforms in the light of the developments in the industry.[80] Apart from the visualization aid, game development platforms can support the design of various interactive game-like architectural environments. The platforms use real-time rendering for dynamic photo-realistic visualization of the 3D models. Immersive experiences can be created mainly by using several game development platforms. For the HoloArch project, Unity game development platform was selected because of its prominent features among the other opponents in the industry;

- Unity environment is the natural development platform for Microsoft HoloLens.[81] Unity is the only appropriate platform for developing mixed and VR applications readily for HoloLens. Hence, HoloArch is aimed at proposing different immersive experiences, including VR and MR; the Unity game engine was the most suitable option for the project.
- The Unity game engine is compatible with various platforms. It supports the development of applications for more than 25 platforms, including desktop, mobile, console, web, and more.[82] Particularly for VR, compatible applications can be created for tablets, mobile phones, and computers.
- Unity supports C# programming language. C # is the new generation object-oriented programming language developed by Microsoft. C # is derived from

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[80] Stefan Boeykens, "Using 3D Design Software, BIM and Game Engines for Architectural Historical Reconstruction," in *Designing Together - Proceedings of the 14th International Conference on Computer Aided Architectural Design Futures*, 2011, 493–509, https://lirias.kuleuven.be/handle/123456789/306891.
[81] Microsoft Inc., "Microsoft/MixedRealityToolkit-Unity," Github.com, 2019.
[82] Ibid, 71.

the two most commonly used software languages, C and C ++, in the software industry.[83] It is also one of the languages developed for Microsoft .NET Framework technology, where various built applications can be run.[84] Since the developers have a background in C#, manipulating, controlling, and problem-solving within this environment became manageable.

- Unity is an open-source and a commonly used software development tool for VR and AR. As of 2018, almost 60% of the current VR and AR applications were prepared by using Unity.[85] The reason why this platform is preferred by developers can be explained by its free, simple, compact, and multipurpose nature.[86] Hence, it is an open-source platform a significant number of developers can work in collaboration without paying any additional cost to the engine itself.[87]

In conclusion, the abovementioned selections shaped the HoloArch project's framework. HoloArch uses Autodesk Revit as a base BIM environment, concentrates on the performative daylighting design of the buildings, and is developed for HTC Vive and Microsoft HoloLens users to provide VR and MR experiences by using Unity game engine.

### 3.2 Software Development Process Model: Spiral

After determining the general outline of the project, the selection of the methodological model, which is essential for the development of the application, was

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[83] John Hunt, "An Introduction to C#," in *Guide to C# and Object Orientation*, 2002, 47–52, https://doi.org/10.1007/978-1-4471-0193-2_5.
[84] Ibid, 71.
[85] Robin Marvin, "How Unity Is Building Its Future on AR, VR, and AI - PCMag UK," uk.Pcmag.com, 2018.
[86] Unity Technology, "Unity 3D," Unity Technology, 2018, https://doi.org/10.3969/j.issn.1002-6673.2014.04.028.
[87] Andres Navarro, Juan Vicente, and Octavio Rios, "Open Source 3D Game Engines for Serious Games Modeling," in *Modeling and Simulation in Engineering*, 2012, https://doi.org/10.5772/29744.

decided. Even though the general context of the project was agreed on at the beginning, the detailed requirements of HoloArch's contents, its features, actions, data integration methods, and data workflows were not known precisely. In the beginning, the problems and limitations of the platforms and possible user reactions were not able to be estimated.

For implementing HoloArch, there are several methodologies to choose from System Development Life Cycle (SDLC) models that include Agile, Iterative, Waterfall, Spiral, and various other methodologies.[88] For the software development process model, the spiral approach was found compossible by the developers because this approach does not ask for precise tool requirements at the beginning of the development process. The spiral model uses a dynamic, iterative, and recursive approach rather than a linear approach.[89] The requirements in the spiral approach are tended to be revised along with time until the software becomes efficient enough to meet with the specified satisfaction level of the developers.[90] This approach is also called as Rapid Prototyping, where user feedback and prototyping is placed in the center of the development process.[91] According to the obtained feedback from repetitive user evaluation studies, any improvement or revision in the software can be accomplished in the next loop, which represents the upcoming version of the software.The HoloArch project was initiated as an ever-growing and evolving system throughout the development process. The creation, improvement, planning, evaluation, and design of the system are interconnected and these stages are growing and expanding by depending on each other. The game-changing decisions were the

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88 Mohammed, Nabil, and Ali Govardhan Munassar. "A Comparison Between Five Models Of Software Engineering." *International Journal of Computer Science Issues* 7, no. 5 (2010): 94–101.

89 Keith Dowding and Brooke C. Greene, "Spiral Model," in *Encyclopedia of Power*, 2012, https://doi.org/10.4135/9781412994088.n345.

90 Paul E. McMahon, "Bridging Agile and Traditional Development Methods: A Project Management Perspective," in *Software Management, Seventh Edition*, 2007, 49–53, https://doi.org/10.1109/9780470049167.ch2.

91 Ibid, 88.

usual part of the project because the precise tool requirements were not able to be attained at the beginning of the project. The spiral approach was adapted because the HoloArch project was wanted to be as flexible as possible. The spiral model allowed HoloArch to be an ever-shifting tool where its possibilities and potentials rose to the surface on its own motion. In this way, HoloArch was enhanced, expanded, and has grown beyond the expectations of the developers throughout the process without the restrictions of any pre-determined requirements (*Figure 3.4*).

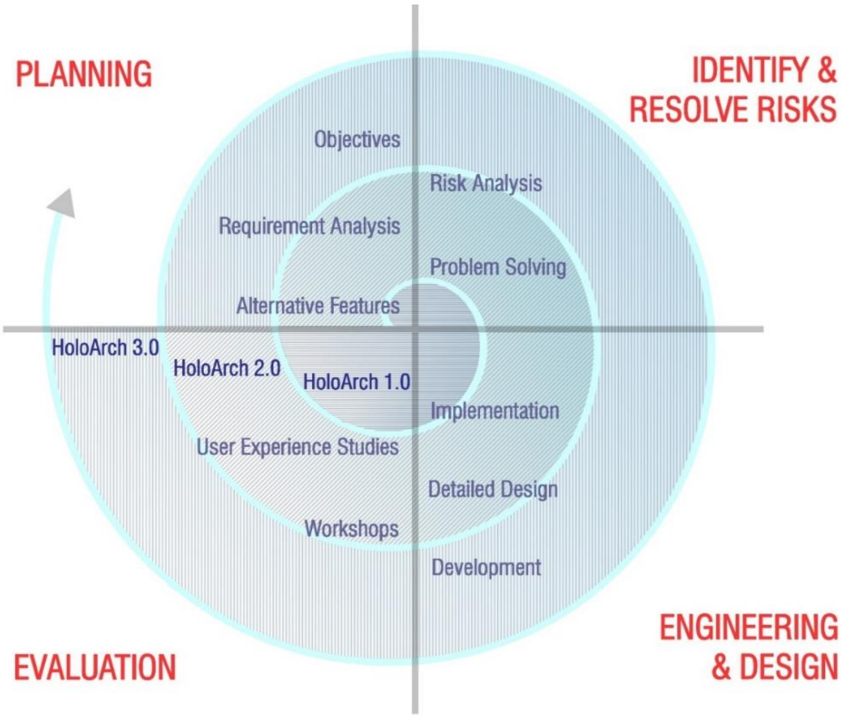


*Figure 3.4.* Spiral software development process model[92] for HoloArch

By adopting the spiral model, HoloArch's first version, named 1.0, was planned, analyzed, designed by the developers, and evaluated by users in an international workshop taken place in Lisbon, Portugal. After the obtained feedback from the

[92] Ibid, 90.

participants, re-planning, re-analyzing, and redesign of HoloArch was performed for the second version and again re-evaluated in a national workshop. This repetitive process was iterated until the third and final version of HoloArch, which is 3.0.

## 3.3 Adapted Immersive Technologies

The HoloArch project was developed for immersive environments. In *Figure 3.5*, the classification of the HoloArch versions under the immersive environment types can be seen.

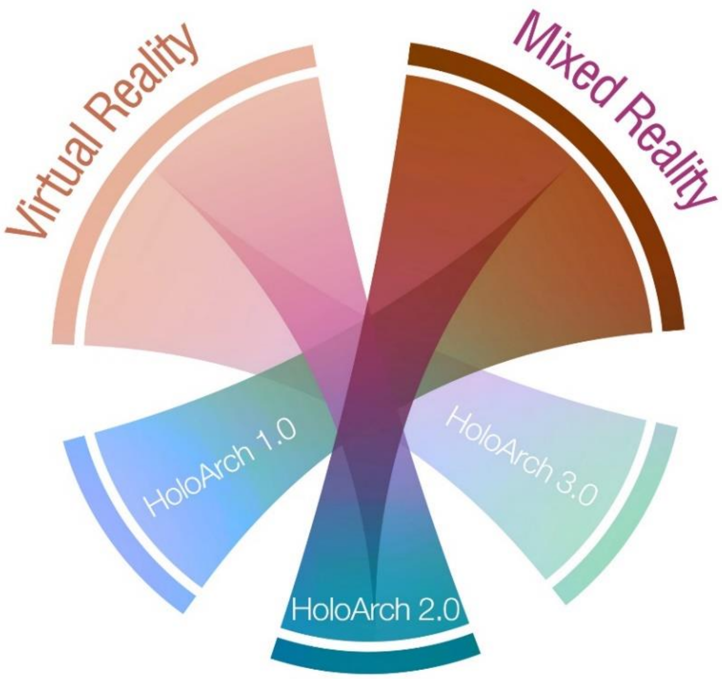


*Figure 3.5.* A digram of HoloArch versions

For finding the most appropriate and suitable environment for HoloArch, several user experiments were performed. The first version of HoloArch was designed only for the MR platform because of the curiosity and excitement of the developers for the new MR technology. However, the first workshop participants were not very satisfied with Microsoft HoloLens along with HoloArch 1.0, as it was discussed thoroughly in Chapter 4.1. For the second workshop, which was taken place in METU, both of the immersive environments were implemented for HoloArch 2.0. Moreover, the workshop also hosted a comparative user study between MR and VR environments and devices, along with HoloArch 2.0's user experience (UX) study. The feedback obtained from the second user study's participants revealed that the VR appliance HTC Vive tends to be preferable as opposed to Microsoft HoloLens. In other words, the majority of the comparative questionnaire items were answered in favor of virtual reality with HTC Vive against mixed reality with Microsoft HoloLens. As a consequence, the last version of the HoloArch (3.0) is adapted to VR only. The HoloArch project's each version and its user studies can be seen in *Figure 3.6*.

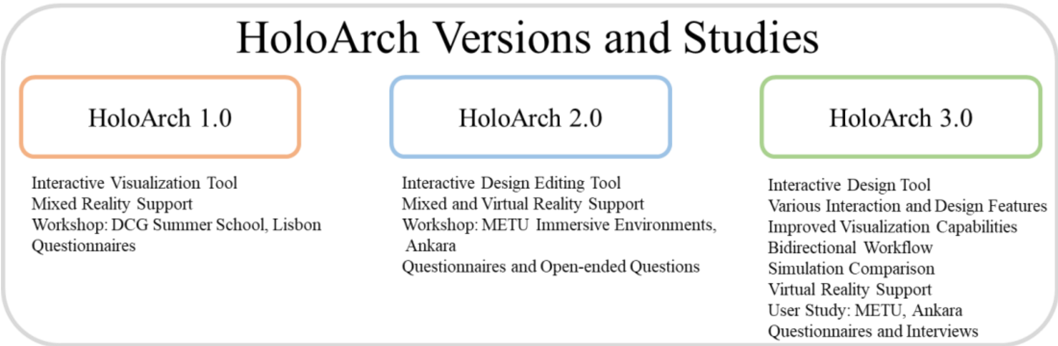


*Figure 3.6.* A digram of HoloArch versions and studies

## 3.4 The Final Requirements

The chosen spiral method does not dictate certain decisions for the software requirements at the beginning; instead, the requirements are self-determined automatically throughout the development process. After two workshops were performed, HoloArch's framework and capabilities were able to be structured more or less. For HoloArch 3.0, final requirements emerged as follows from the lessons learned in the previous UX studies;

- An interoperable and bi-directional workflow between BIM (Revit) and game engine (Unity) platforms shall be solved without any substantial data loss. The modes of interoperability between various software tools and file formats used in architectural design still are not standardized. Data loss during transfer is still prevalent, and attempts to develop a standard data format is not accomplished.[93] Since there are numerous software programs in architecture that serve particular demands, the data loss during the transfer is inevitable, and these limitations hinder architectural processes.
- A workflow that supports a continuous design process between Revit and Unity shall be achieved.
- HoloArch shall provide appropriate daylighting simulation visualizations to guide the users for their performative actions. The complexity of the daylighting simulations should be easy enough for users to make inferences about the daylighting performance of a building. The visualization of the simulation grid should not be overwhelmingly enormous and distractingly colorful for VR.
- The user interface (UI) of HoloArch shall be aesthetically pleasing, categorically classified, and easy to interact with for better UX. Users shall access it without any additional help for their intended actions. The UI design of immersive tools is one of the most crucial parts of the development process because it directly affects the tool's usability and user engagement[94].
- Various alternative performative design actions shall be defined for users that allow reflecting of their performative thinking without significant limitations. Users may change their buildings freely by functioning their preferred

[93] Robert J. Hitchcock and Justin Wong, "Transforming IFC Architectural View BIMs for Energy Simulation: 2011," in *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, 2011.
[94] Fabio Bruno and Maurizio Muzzupappa, "Product Interface Design: A Participatory Approach Based on Virtual Reality," *International Journal of Human Computer Studies*, 2010, https://doi.org/10.1016/j.ijhcs.2009.12.004.

intervention methods among the numerous defined design actions in HoloArch.

- The defined performative actions shall allow direct editing of; building elements, landscape, planning of spaces, materials, building orientation. Interaction between the user and the environment shall be improved and enhanced by providing feedback.
- The visualization of BIM data shall be informative to provide properties of building elements.
- The visualization of the building shall remain abstract without realistic materials in order to prevent confusion with colorful analysis visualization.
- The tool's control mechanisms shall be designed in a way that shall be felt natural and intuitive for the users.
- Actions for understanding and exploring the virtual scene shall be provided. Users shall walk around their buildings, teleport different places, or enter inside of their buildings conveniently.
- HoloArch shall provide different architectural scale options for the realization of a more perceptive design. Simultaneously switching between different scales shall allow the users to think, see, navigate, and design more efficiently.

According to the emerged requirements after the workshops, HoloArch 3.0 was redesigned, planned, and eventually finalized as a completed VR tool.

### 3.5 Development of HoloArch

The environment allows users to interact, edit, visualize, manipulate, and review architectural models and to perform daylighting design in immersive environments. In contrast with the existing immersive tools in architecture, HoloArch offers continuous bidirectional workflow between BIM tools and game engines. Iterative export-import processes enable designers to work in different design environments without data loss. The finalized flowchart of HoloArch can be seen in *Figure 3.7.*

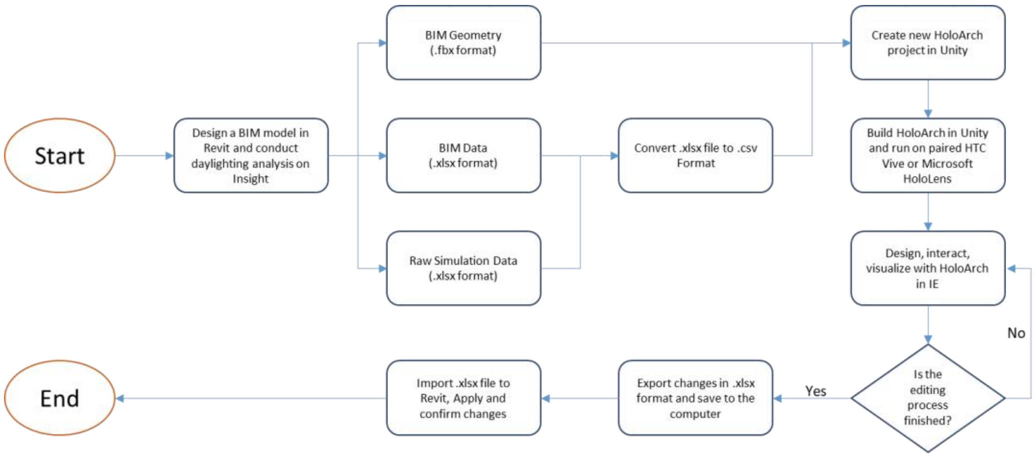


*Figure 3.7.* HoloArch's finalized flowchart

### 3.5.1 System Workflow

HoloArch presents a smooth and reversible workflow and allows its users to bridge the gap between BIM tools and game engines. Different data transfer procedures were followed in the integration of the involved tools. Since only HoloArch 3.0 is a bi-directional and completed tool, the following transfer methods are based on its workflow (*Figure 3.8).*

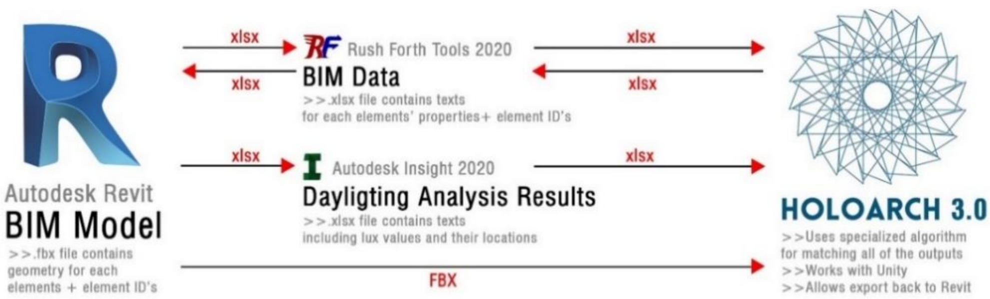


*Figure 3.8.* Communication between the involved tools

#### 3.5.1.1 Autodesk Revit to Unity: Building Geometry Transfer Methods

HoloArch should propose not only the visualization of the 3D models but also visualize 3D model's unique element properties to be able to edit models in immersive environments. For that purpose, the building model transferred from Revit to Unity needs to enable users to access and to select each imported element without loss.[95] The exported geometry in Revit should at least have the element Ids and correct geometries grouped under element categories.

Autodesk Revit 2017 software supports to export DWG, DXF, DGN, ACIS SAT, FBX, DWFX, IFC, GBXML file formats. These file formats can support the work on different software tools for uninterrupted workflow. However, some of the file formats that are compatible with Revit are not compatible with Unity's API due to the different functionalities they address. In order to find the best solution for a smooth transition between these two separate platforms, the bridging file format needs to be determined.

Data integration between the two platforms requires the use of a standard file format. FBX (Filmbox) file format was selected as the primary 3D geometry transfer method between Unity and Revit. This file format can provide both unique Element IDs for each element and also group elements according to their categories. FBX files can be exported directly from Revit's interface or with the support of various other plug-ins such as Archilizer, TwinMotion's Dynamic Link, and SimLab Fbx exporters (*Figure 3.9*). These plug-ins are generally designed for their developers' standalone applications since the exported results generally serve the needs of the developer applications.

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[95] Oguzcan Ergun et al., "Architectural Design in Virtual Reality and Mixed Reality Environments: A Comparative Analysis," in *26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019 - Proceedings*, 2019, 914–15, https://doi.org/10.1109/VR.2019.8798180.

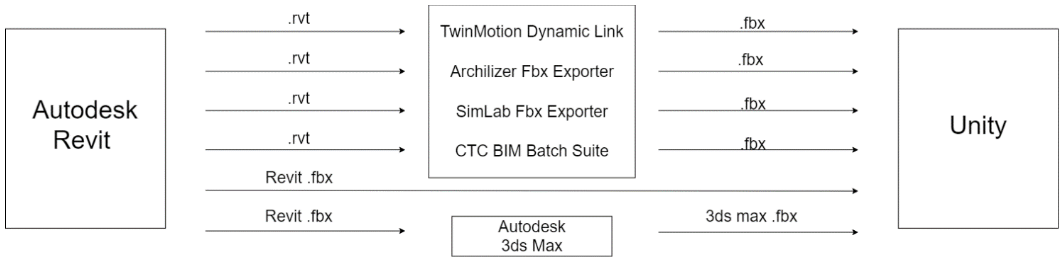


*Figure 3.9.* Fbx export methods from Revit to Unity

In conclusion, users can export their designed geometry directly through Revit's own FBX export command. This type of geometry transfer method was considered as the best solution in the frame of the current capabilities of both applications by providing precise geometry along with the elements' Revit IDs.

#### 3.5.1.2 Autodesk Revit to Unity: BIM Data Transfer Methods

The advantage of BIM tools relies on its storage capabilities that enable archiving vast amounts of data related to building components. These stored data can be used both during the design process and throughout the project's life cycle.[96] While transferring the model, the previously mentioned available transfer file formats do not contain elements' data. For this reason, another method was followed in order to reach the elements' BIM data. For this problem, a commercial plug-in for Revit called Rushforth Tools was tested and decided to be used in the HoloArch's workflow.[97] *Rushforth Tools*[98] can export selected type parameters and its contents of the BIM model into an Excel file. These type parameters also include elements' type IDs, which are identical to the element IDs in the exported FBX file. For this

[96] Jing Du et al., "Zero Latency: Real-Time Synchronization of BIM Data in Virtual Reality for Collaborative Decision-Making," *Automation in Construction*, 2018, https://doi.org/10.1016/j.autcon.2017.10.009.
[97] Ibid, 3.
[98] *RushForth Tools*, retrieved from http://www.rushforthprojects.com/ (December 15, 2018)

study, the relevant parameters of the elements are determined and exported with their unique IDs by using the plug-in for Revit.[99]

A script was coded by the developers in the C# programming language to assign BIM data from the Excel file to the elements in the FBX file. HoloArch can automatically match Excel BIM data and FBX BIM geometry by using element IDs. In this way, BIM data and the geometry are matched for the visualization of the architectural model.

A specific button in the UI was assigned for displaying elements' BIM data in HoloArch. When the users click on a building element and select this button, a popup screen shows up indicating the associated element's filtered type parameters. The filtration was made according to parameters' relevancy to the daylighting. This kind of interaction paves the way for useful possibilities in terms of data visualization.

#### 3.5.1.3 Autodesk Revit to Unity: Transfer Method for Simulation Data

Insight Lighting Analysis[100], which is an in-built plug-in for Revit, conducts daylighting analysis and visualizes the results in 2D as an overlay layer to building geometry.[101] Insight also creates automated scheduling to guide users by means of daylighting in their design. As of 2019, the following analysis types are possible: Illuminance Analysis, Daylight Autonomy, LEED 2009 IEQc8, LEED v4 EQc7, Solar Access[102]. One of the aims of this project is to offer an immersive and interactive visualization environment for performative analysis' results that contain a large amount of data that are generally difficult to grasp and examine.

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[99] Ibid, 3.
[100]"Lighting Analysis | Insight 360." Accessed February 9, 2020. https://blogs.autodesk.com/insight/category/lighting-anaylsis/.
[101] Ibid, 95.
[102] "Free Software for Students & Educators | Revit | Autodesk." Accessed February 9, 2020. https://www.autodesk.com/education/free-software/revit.

Autodesk Insight is able to export the numerical data behind the 2D analysis visualization.[103] In these raw data files, each simulation grids' location (x, y, z) and their calculated values in Lux are provided. Autodesk Insight is able to export raw data analysis results only for the specific analysis types such as illumination, LEED 2009 IEQc8, and LEED v4 EQc7 analyses. The exported raw data file format comes as an Excel file, and the developed C# algorithm in HoloArch takes this Excel file and convert each simulation point as spheres. The spheres are mapped in the confinements of the building floor area. The spheres are levitated and change colors according to the intensity of the Lux value *(Figure 3.10).* While reddish colors represent high, bluish colors represent low Lux levels. HoloArch 3.0 can visualize four simulation results at the same time and allows users to make a comparison between different simulations.

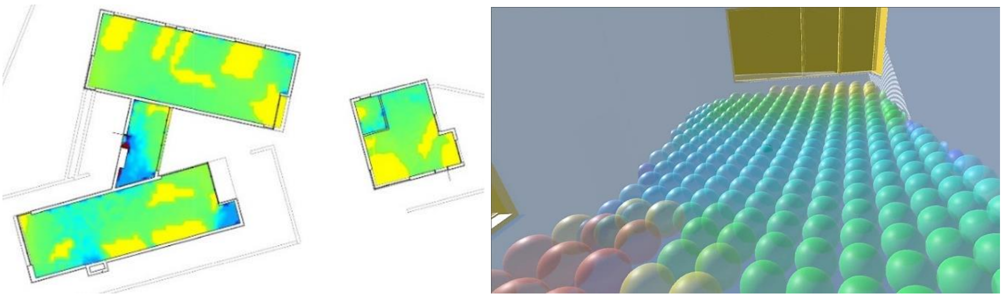

*Figure 3.10.* Autodesk Revit Insight and HoloArch's daylighting visualization

#### 3.5.1.4 Unity to Autodesk Revit: Geometry and Data Transfer Methods

Among the capabilities of the HoloArch project, another prominent feature of HoloArch is the reversible workflow between Autodesk Revit and Unity. For achieving optimal daylighting illumination, users can edit their architectural models according to the 3D daylighting analysis. After the editing process is completed in HoloArch, users can continue to work on Autodesk Revit for further detailing,

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[103] Ibid, 95.

finalizing their building designs, and preparing blueprints. HoloArch overwrites all the edited model parameters into the same Excel file that was used earlier at the beginning of the workflow. In the final step, the updated Excel file is imported back into Autodesk Revit.

The imported Excel file enables the automation of revising the pre-designed Revit geometry and BIM data according to the changed parameters. This cyclic approach enables an uninterrupted design process and allows designers to work in various design environments without data loss. This distinctive feature of HoloArch differs from the other immersive tools in the field of architecture and proposes a novel approach for continuous workflow between the platforms.

However, the capabilities of this reversible workflow limited only for editable type parameters allowed by the Revit software. Revit consists of two sorts of type parameters: The read-only and the editable parameters. The read-only parameters are not allowed to be edited from external interventions because these parameters are based on complex interdependent calculations. These parameters are not changeable and do not respond to the conversion of their numeric values. For instance, if a user would like to change the area of the room by revising its area value, Revit does not let it happen since the area parameter is a consequence of width and length parameters' multiplication. These types of dependent parameters in Revit named "Read-only". In the HoloArch project, the responsive and unresponsive parameters were investigated; the read-only parameters are excluded, and only the editable type parameters were adapted to HoloArch. The editable parameters were filtered according to their relevancy to the daylighting design. HoloArch's design actions were designed according to these editable parameters because of the constraints caused by Revit's working principle. As an example, a window category's editable parameters can be seen in *Figure 3.11*.

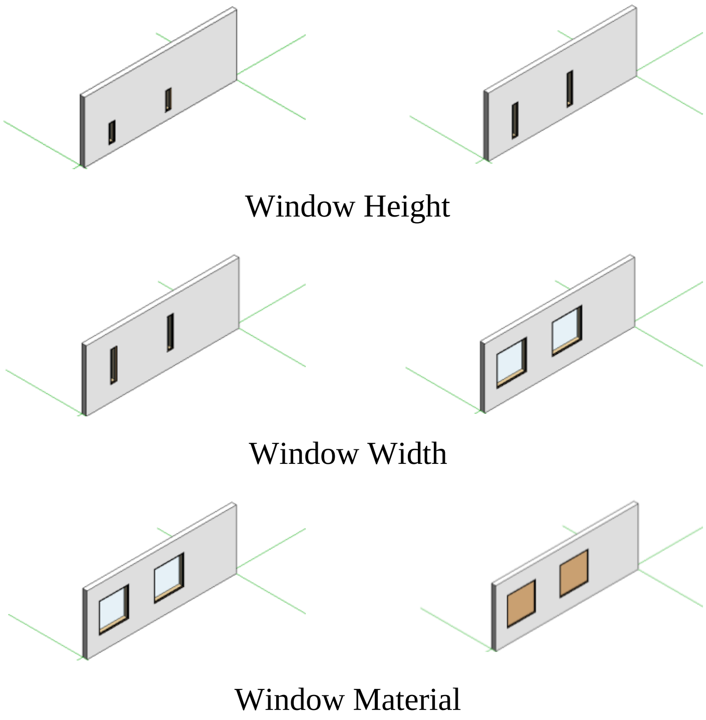


*Figure 3.11.* Some of the editable type parameters of window families

### 3.5.2 HoloArch's Supported Features

The featured interactions were designed according to their relation with daylighting design, architectural exploration, and visualization (*Figure 3.12*). HoloArch 3.0 has various interactive actions, including; editing building elements, furbishing, navigating around, placing objects, and visualizing various building-related data for supporting users' performative daylighting design activity. HoloArch's supported actions were classified under five primary tabs in the UI in order to ease the tool's usability. These tabs and their containing actions are expounded below;


*Figure 3.12.* HoloArch has various actions for daylighting design

#### 3.5.2.1 Visualize Analyses

**Visualize Analysis Results:** The actions were designed to allow users to visualize daylighting simulation results in 3D. When activated, the simulation results are visualized as colorful levitating spheres inside the building. Simultaneously, a graph pops up for informing users about the extreme-ends of the illumination levels of a building. HoloArch averages the illumination levels on the equinox days and visualizes the analysis data for both morning and afternoon. In this way, users can alter a building's design by interpreting the analysis results for the most crucial two different time steps.

**Wireframe rendering:** Users can change the view style of the environment from conceptual to wireframe style (*Figure 3.13*). This action was defined to ease the visibility of the analysis results more conveniently from outside of a building.

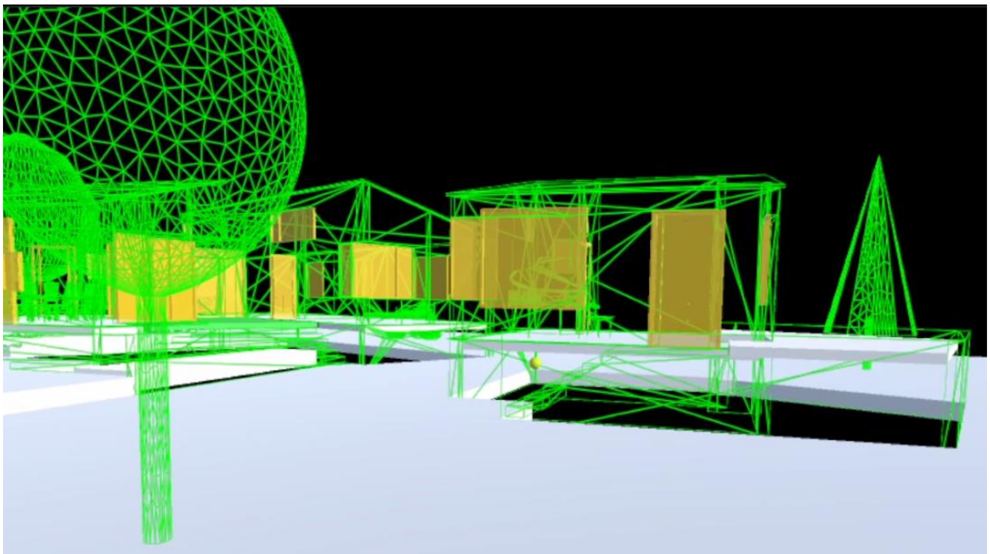

*Figure 3.13.* Wireframe view style

**Shadow visualization:** According to the selected analysis time and site location, HoloArch casts a shadow to the environment as additional support for guiding users in terms of daylight conditions.

**Removing the simulation grid:** Hence the simulation data consists of hundreds of spheres; this might affect the performance of HoloArch. This action speeds up the display's frame rate by hiding the simulation results temporarily.

**Hide Building Envelope:** Similar to wireframe rendering, this action was provided to ease the navigation in the environment (*Figure 3.14*). Users can hide wall and roof categories for focusing only on the fenestration and door elements (*Figure 3.15*).

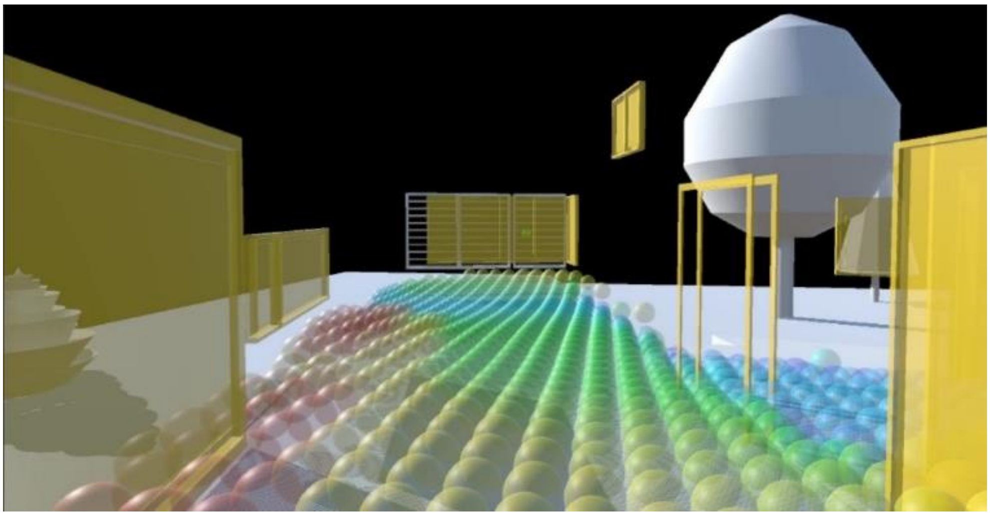

*Figure 3.14.* Hiding envelope allows easy access to simulation spheres

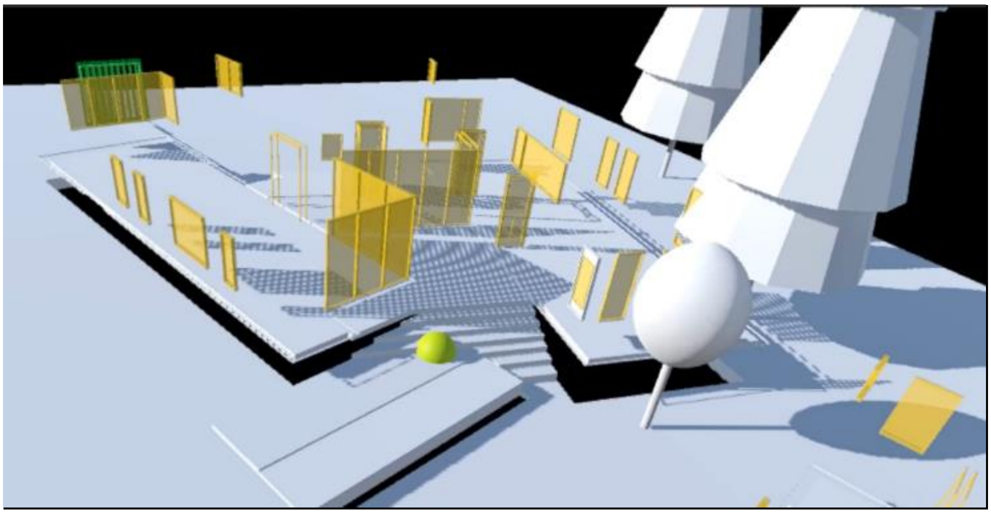

*Figure 3.15.* Hiding envelope elements excludes fenestration and door families

#### 3.5.2.2 Visualize BIM Data

Users can access the properties of a selected building element by visualizing its BIM Data. Since BIM elements consist of embedded numerous parameters and specifications, only the selected parameters are visualized in HoloArch. The selection of the parameters was performed by filtering relevant parameters for the daylighting, spatial, and visual aspects of buildings. Since the resolution of the HTC Vive gadget is low, the use of written information was limited for the readability of the data *Figure 3.16.*


*Figure 3.16.* BIM data visualization of the selected window element

### 3.5.2.3 Edit and Change

The actions allowing for daylighting design were defined mainly under this tab. Users can manipulate the characteristics of the building elements by editing their dimensions, materials, rotation degrees, and can change the entire building's orientation.

**Change Materials:** Users can play with the materials of glazing, frame, and surface materials of a window, shading device, and door category. In addition, users can control and edit the transmissivity of landscape elements, including trees, bushes, and shrubs. Users can specify whether the used landscape elements are evergreen or deciduous for daylighting design of the interior spaces. These actions are provided to allow users to control daylight in an alternative way when they do not wish to interfere with the architecture of buildings. However, no direct visual feedback is provided for the material actions; instead, the material changes are reflected on only BIM Data and the final design parameters. (*Figure 3.17*)


*Figure 3.17.* HoloArch allows users to change the materials of some building elements

The provided material set is in sync with the Revit project template, which means that all the provided materials in HoloArch have correspondence in Revit as well.

- For glass materials four different materials are defined;
  1. 60% transitivity, Single Pane 8 mm,
  2. 70% transitivity, Single Pane 3 mm,
  3. 90% transitivity, Single Pane 3 mm,
  4. 50% transitivity, Double Pane 5 mm,
- For frame materials, four different materials for windows, doors, and shading devices are defined;
  1. 20% reflectivity, polished timber,
  2. 0% reflectivity, Timber,
  3. 35% reflectivity, PVC,
  4. 55% reflectivity, Iron,
- The transmittance of the landscape elements is provided with four different materials that have;
  1. 49% transitivity:

2. 35% transitivity,
3. 17% transitivity,
4. 0% transitivity,

**Edit Elements:** Users can change the dimensions of opening components' widths and heights, including windows and doors, by selecting actions under this tab (*Figure 3.18*). These actions are provided to give users opportunities to change and to redesign the architecture of buildings according to daylighting simulations. Users can resize the area of openings either to introduce more light to spaces or to limit the penetration of excessive solar rays to the interior spaces.

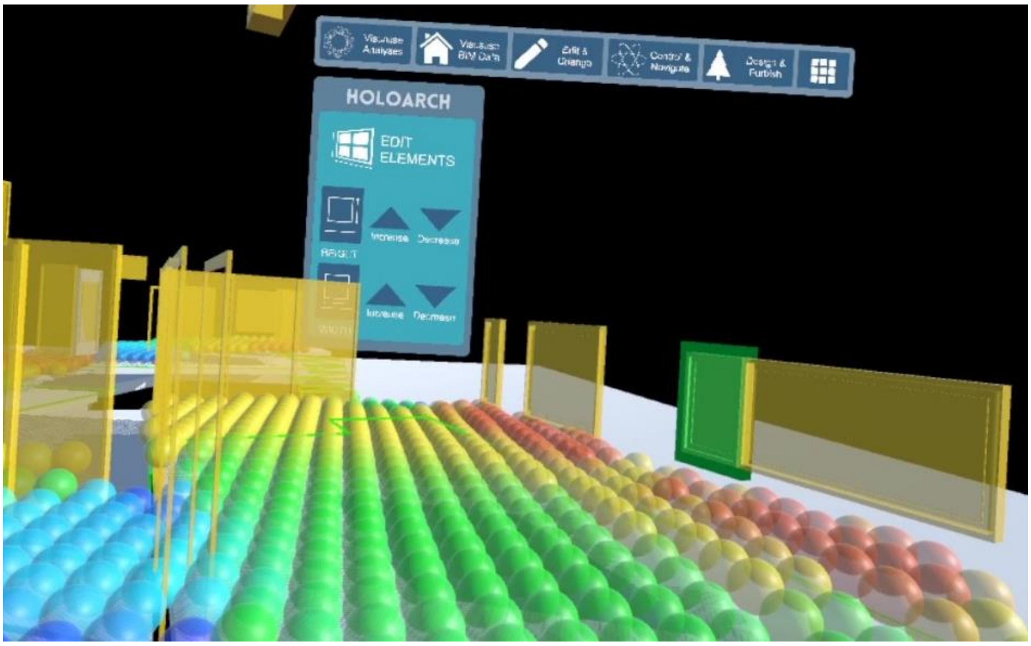


*Figure 3.18.* Resizing windows according to daylighting simulations

**Rotate Elements:** HoloArch allows users to place objects, but the placed objects may not always come aligned to the boundaries of rooms. In order to place objects aligned to reference surfaces, a rotation command allowing four different increment degrees (*Figure 3.19*) is defined to HoloArch.

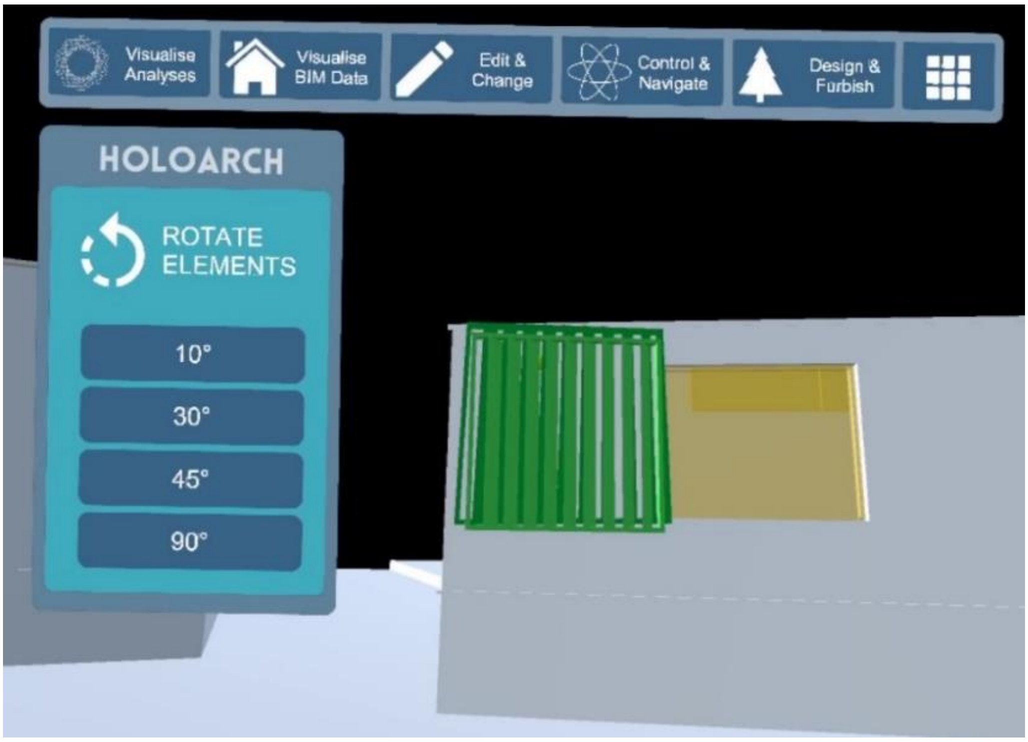


*Figure 3.19.* Rotating a shading element

**Apply Changes:** At the end of the experience in HoloArch, users can apply all of the performed changes in the design to an Excel file for initiating the transfer of final design to the BIM environment. With this feature, further detailing and precise fine-tuning in the BIM environment becomes available for users without any data loss.

#### 3.5.2.4 Control and Navigate

**Scale:** Users can change a building's scale simultaneously, and can switch back in forth between the different scales easily. The most commonly used architectural scales are provided, including 1/1, 1/2, 1/5, 1/20, 1/50 (*Figure 3.20*). Smaller scales (e.g., 1/100, 1/200) were excluded in HoloArch because over-scaled geometries in immersive environments could cause visibility problems.

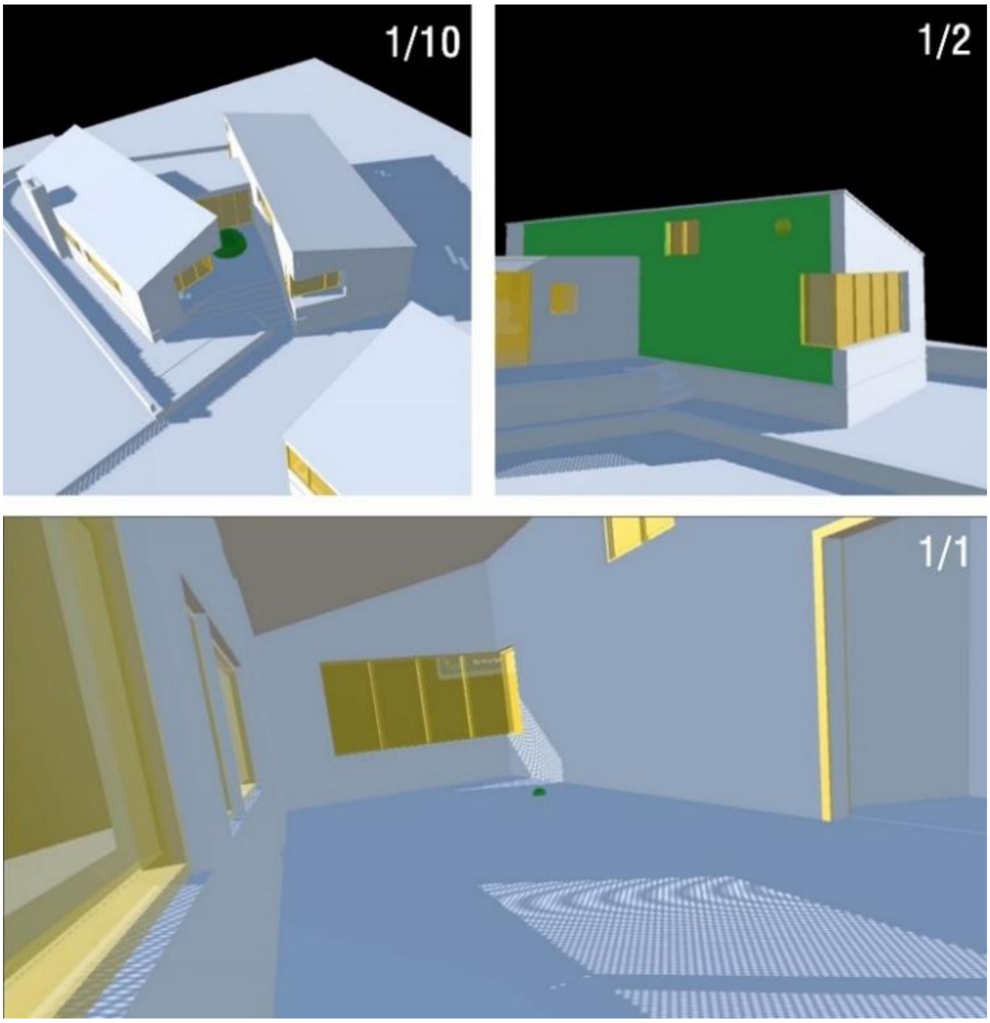


*Figure 3.20.* Different scales offer different opportunities

**Change the UI Position:** Users can change the UI position to their desired locations. This feature is provided when users could not reach to the UI because of the occlusion caused by building geometry. Until the third version of HoloArch, this feature was the part of the UI; afterward, it was assigned as a button directly in the HTC Vive's controllers for easing the tool's usability.

**Change Building Orientation:** An option to change the orientation of a building is also provided to users as an additional alternative for daylighting design. The action functions similar to the rotate feature mentioned in earlier sections. A compass also provided for direction finding, which can be seen in *Figure 3.21*. Although this action is not useful for the completed buildings, it is an efficient feature for the ones in early design stages.[104]

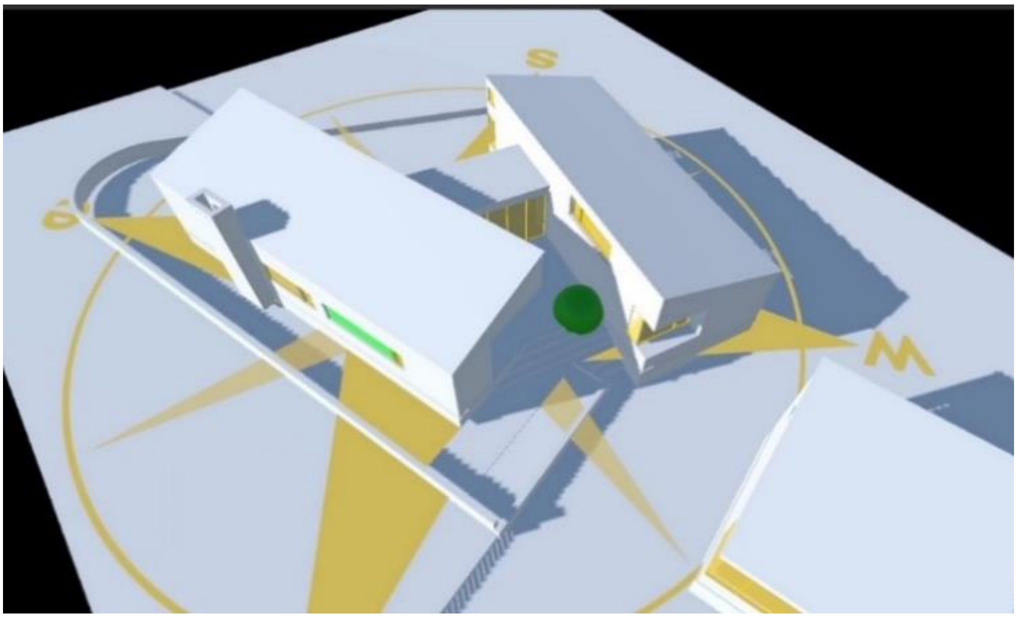


*Figure 3.21.* A compass pops out when the building orientation command is activated

#### 3.5.2.5 Design and Furbish Tab

Under this tab, users can place existing family types assigned to the HoloArch Project according to the daylighting simulations for shading design, space, and landscape planning. The placeable elements in HoloArch have correspondence as objects clustered under “entourage”, “furniture” and “generic model” family types in Revit. Some of the catalog elements can be seen in *Figure 3.22*.

[104]Elizabeth Lewis, “Building Orientation,” in *Sustainaspeak*, 2018, 42–45, https://doi.org/10.4324/9781315270326-26.

*Figure 3.22.* Placeable object logos

**Space Planning:** Users can re-design the existing layout of a building by placing furniture objects. The furniture catalog consisting of 15 unique objects, was prepared to give users opportunities to re-plan wet spaces, living room, bedroom, office, and kitchen spaces in a building by interpreting the simulation results. For instance, when red spheres are intensified somewhere in a building, users may not want to place a TV unit in that particular area because of the possible glare issues. This kind of feature is thought to be useful for daylighting oriented space-planning and is made available for HoloArch. When users perform the daylighting design of a building, this feature may lead users not only to focus on exterior architecture but also to reshape the organization inside the building as well.[105] In *Figure 3.23*, a living room organization in a building according to daylighting simulations can be seen.

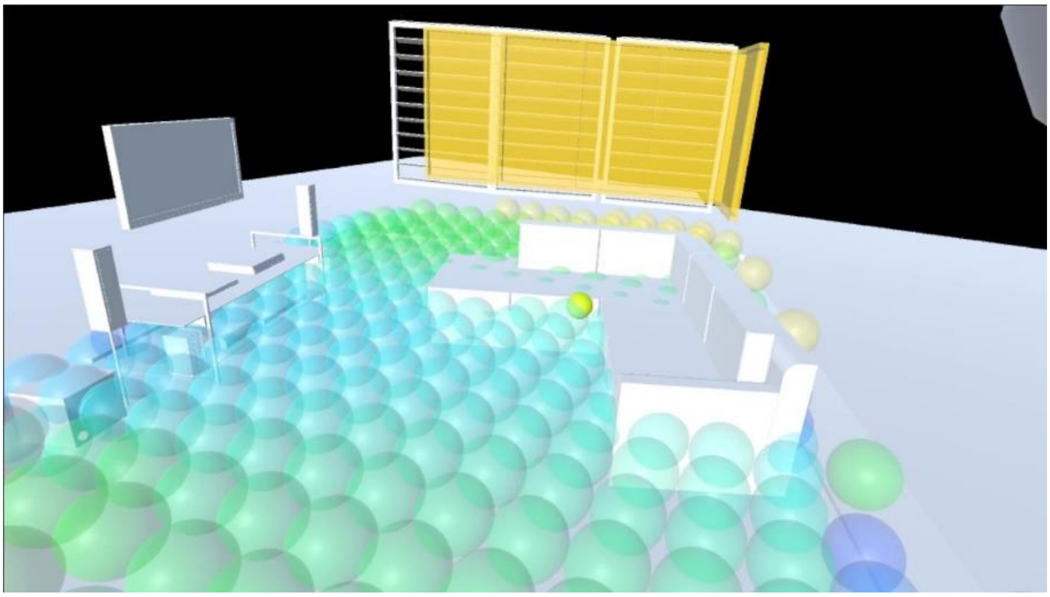

*Figure 3.23.* Space planning according to daylighting simulations

**Landscape Design:** Another critical aspect that affects the daylighting performance of buildings is landscape design. Plants are an essential part of an environmental building and have a direct influence on energy consumption, comfort levels, and lighting design of the buildings.[106] In HoloArch, 5 different plant types in various sizes are provided, including big or small canopied trees, shrubs, and bushes. Users can locate these plant objects in front of the problematically daylit areas in a building and can assign different transitivity materials to control how many solar rays can be able to penetrate into a building (*Figure 3.24*).

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[105] Kevin G. Van Den Wymelenberg, "Visual Comfort, Discomfort Glare, and Occupant Fenestration Control: Developing a Research Agenda," *LEUKOS - Journal of Illuminating Engineering Society of North America* 10, no. 4 (2014): 207–21, https://doi.org/10.1080/15502724.2014.939004.
[106] Nazire Papatya Seçkin, "Environmental Control in Architecture by Landscape Design," *A/Z ITU Journal of the Faculty of Architecture*, 2018, https://doi.org/10.5505/itujfa.2018.90022.

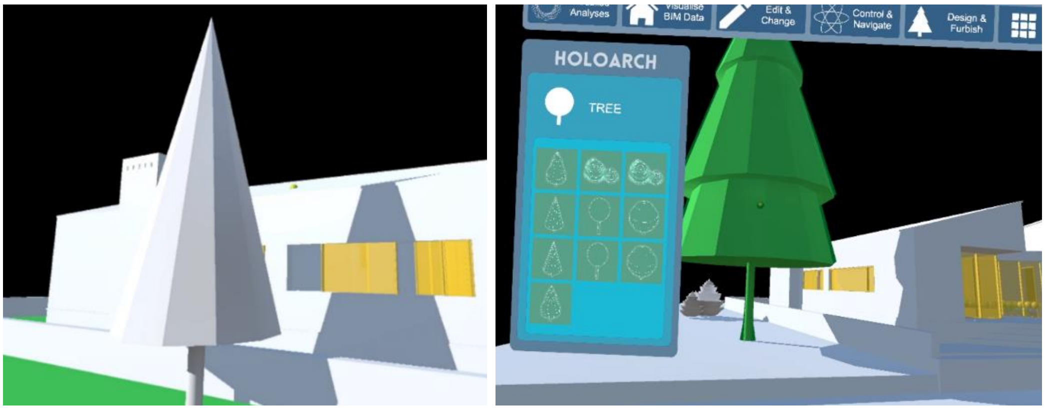


*Figure 3.24.* HoloArch allows users to place landscape elements to their projects

**Daylighting Control:** Exterior shading elements directly affect the daylighting introduced to interior spaces. [107] Since HoloArch is a daylighting design tool, shading devices were the fundamental elements to control solar rays. While horizontal louvers have the maximum impact on blocking the rays when placed in front of the windows facing the south direction, vertical louvers are suitable for east and west directions.[108] The shading catalog consists of  vertical and horizontal louvers for blocking excessive insolation inside a building.

### 3.5.3 Version Differences of HoloArch

As a consequence of adopting the spiral development model, different versions of HoloArch emerged chronically as HoloArch 1.0, 2.0, and 3.0. As stated before, while HoloArch 1.0 is available only for MR, HoloArch 2.0 is for both VR and MR; and HoloArch 3.0 is only for VR environments. The differences in versions can be

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[107] Ahmed A.Y. Freewan, "Impact of External Shading Devices on Thermal and Daylighting Performance of Offices in Hot Climate Regions," *Solar Energy* 102 (2014): 14–30, https://doi.org/10.1016/j.solener.2014.01.009.
[108] Nedhal A. Al-Tamimi and Sharifah Fairuz Syed Fadzil, "The Potential of Shading Devices for Temperature Reduction in High-Rise Residential Buildings in the Tropics," in *Procedia Engineering*, vol. 21, 2011, 273–82, https://doi.org/10.1016/j.proeng.2011.11.2015.

noticed explicitly on the tool's interaction-control mechanisms, its available features, and UI design.

**Feature differences (*Figure 3.25*):** HoloArch 1.0 was the initial prototype that offers only unidirectional workflow, visualization of BIM data,

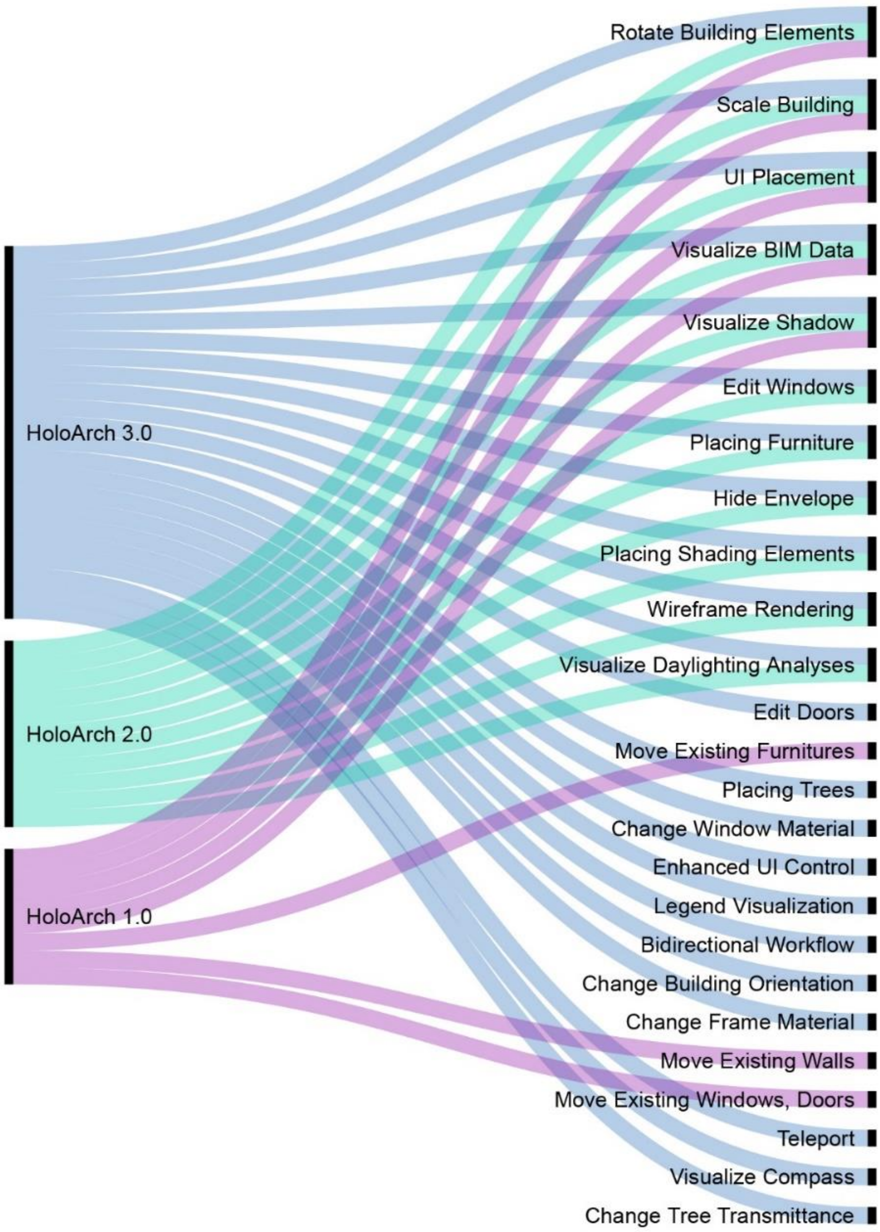


*Figure 3.25.* Feature differences between the versions

and simulation results. Since HoloArch 1.0 is unidirectional, all of the actions performed are captured in the immersive environment. Although this may seem restrictive, the one-way approach can provide users a possibility to alter more smoothly on building geometry. For example, while the 1.0 has displacement actions of wall and window elements, the latest version does not have because of the limitations in the reversible workflow back to Revit. Even though HoloArch 1.0's contributions to the design process are controversial and all of the actions performed cannot be reached again, it serves as an interactive visualization tool. On the other hand, Version 2 serves as a bridge-like mediator between MR and VR environments and allows users to perform a few design actions. To conclude, HoloArch 3.0 is the most advanced and completed version of HoloArch and hosts a great variety of actions compared to the priors.

**Interaction Method Differences:** The type of immersive environment and the selected immersive technology directly affect the control mechanisms and model interaction methods of HoloArch. For HoloLens, the natural interaction method is recommended as using hand gestures and gaze to control the environment. On the other hand, HTC Vive requires its own controllers to be able to interact within the VR environment. In MR environments, users do not need actions such as teleporting and walking since virtual geometry is anchored to the physical world; instead, they can literally walk around geometries as in real-life conditions. On the other hand, in VR environments, users require additional navigation actions to be able to explore the environment because of the short-range capacity trackers of the short-corded HTC Vive gadgets. In order to control the environment, specific actions were assigned to the gadgets controllers. For HoloLens, three different hand gestures were defined, including gaze (to hover the cursor), air tap (for selecting elements or actions), and bloom (for closing the app). For HTC Vive, three buttons on the controller were used to teleport, to select and to change the location of the UI. The representation of the gestures and HTC Vive's controllers can be seen in *Figure 3.26*.

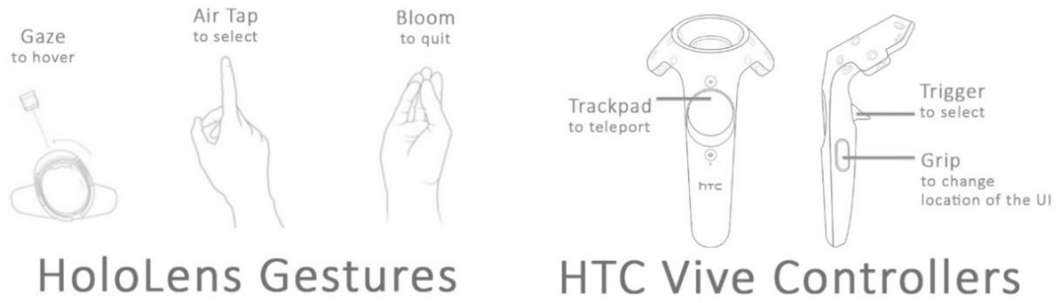


*Figure 3.26.* Environment control for Microsoft HoloLens and HTC Vive

**UI differences:** Another visible difference between the versions can be seen in the UI design of HoloArch. With the newly added features in each version, the user interface changed seriously over the development process. Since the first version had relatively few features, the action buttons could be regularly distributed in the user interface. However, the user interface has become increasingly convoluted with each additional action in HoloArch 2.0. In addition, the design of the UI based on plain texts on generic gray bounding boxes in the earlier versions. In HoloArch 3.0, the actions are clustered under specific categories and enriched with custom-designed logos for a more aesthetically pleasing UI.

For the conclusion of this chapter, a performance-based design tool named HoloArch was developed that allows designers to review architectural design models, simulation results interactively, and to perform design actions. HoloArch expands the current capabilities of the BIM tools and uses multiple modes of visualization techniques. In addition, HoloArch is supported in differently working VR and MR environments and can work bidirectionally with BIM environments. The evaluation of each HoloArch version's potentials and limitations were investigated in the following chapters by conducting workshops and a user study. The visual differences between the UIs can be seen in *Figure 3.27*.

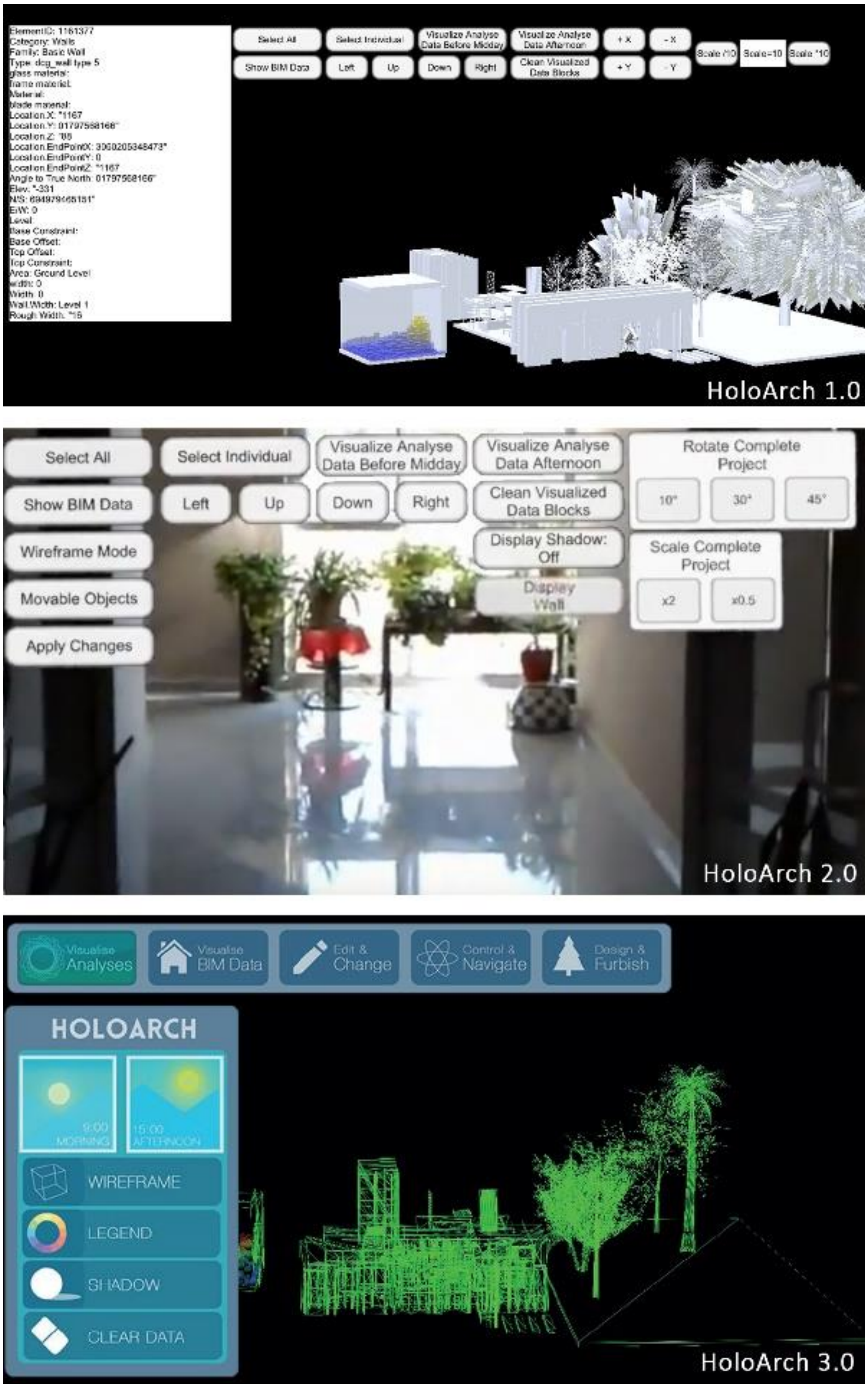


*Figure 3.27.* UI differences between the versions

# CHAPTER 4

# THE WORKSHOPS

## 4.1 DCG Summer School 2018: Immersive and Responsive: Performative Architectural Design in Mixed Reality

The limited research work on the immersive visualization of the performative and architectural simulations in the literature calls for a method for the seamless integration of BIM models and their performative simulations results' visualization to MR environments. In other words, there is a lack of integrated, immersive tools in support of performative architectural design visualization in MR environments. In this regard, HoloArch 1.0 is presented, which allows designers to review architectural design models and simulation results interactively. HoloArch 1.0 integrates various concepts from different design fields, such as daylighting simulations, BIM, and MR technologies (*Figure 4.1*). HoloArch 1.0 aims to expand the current capabilities of the BIM tools and to use multiple modes of visualization techniques to improve the visual perception of designers.

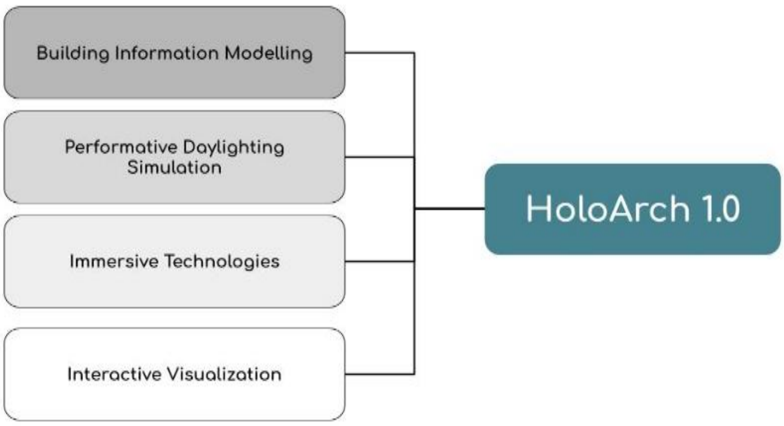


*Figure 4.1.* The topics involved during the development of the proposed tool

### 4.1.1 The Workshop Procedure and Participants

The need for performance-based immersive design tools that support performative design development, reviewing, and design interaction was previously identified. HoloArch 1.0 was developed for the MR environment to address these needs. However, MR is a relatively new field and the previous studies on the matter are limited in architecture-related fields. An MR tool, HoloArch 1.0, can be a solution for increasing visual perception, which plays a significant role in architects' design decisions. For the validation of the tool for the users' visual perception and interaction, a 2.5-day workshop was organized. The workshop was a part of the Design Computation Summer School 2018 (DCG Summer School 2018)[109], organized by the Design Computation Group of the Faculty of Architecture, University of Lisbon, under the title "Immersive and Responsive: Performative Architectural Design in Mixed Reality." *Figure 4.2* shows the participant's photos while they were using HoloArch 1.0 in HoloLens.

*Figure 4.2.* Photos of the participants while they were experiencing HoloArch with MR

The first 1.5 days were dedicated to lectures and hands-on exercises on sustainable design, daylighting, BIM, and MR. Software tutorials were given for Autodesk

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[109] "Immersive and Responsive – Design Computing Summer School 2018," accessed December 25, 2019, http://dcgsummerschool2018.fa.ulisboa.pt/index.php/immersive-and-responsive/.

FormIt[110], Autodesk Revit, and Insight 360[111]. Students were divided into two groups and were asked to design a home office building in two different cities: Cairo and Reykjavik. Each city presents various challenging daylighting conditions due to the different solar illumination they receive. Students initialized the design process by creating mass options on Autodesk FormIt and by selecting one alternative among their mass models. The selected design alternatives were detailed, and daylighting simulations were performed in Autodesk Revit and Insight. The design outputs including the building geometry, BIM data and the simulation results, were transferred to HoloArch. Finally, all participants experienced their design in MR by visualizing, exploring and interacting with their building designs using HoloLens on HoloArch 1.0.

### 4.1.2 The Evaluation

For evaluation, questionnaires with 5 levels Likert Scale (1= Strongly disagree, 2= Disagree, 3= Neither agree nor disagree, 4= Agree, 5= Strongly agree) with optional comment fields are adopted. The neutral level in the questionnaire was determined as 3.0 out of 5.0. A descriptive analysis tool, *IBM SPSS*[112], was used to calculate the mean and the standard deviation values. 36 questions are designed by modifying the standard VR questionnaires. The questionnaire was grouped into two sections: Architectural issues regarding the design perception, model interaction, and Standard

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110 "Autodesk FormIt," Air Conditioning, Heating & Refrigeration News VO - 250, 2013, http://ezproxy.leedsbeckett.ac.uk/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsggo&AN=edsgcl.355867816&site=eds-live&scope=site.

111 Autodesk Inc., "Insight: Building Performance Analysis Software," Autodesk, 2018, https://autodesk.com/products/insight/overview.

112 IBM, "SPSS Software - Australia | IBM," accessed December 25, 2019, https://www.ibm.com/au-en/analytics/spss-statistics-software?cm_mmc=Search_Google-_-Hybrid+Cloud_Data+Science-_-WW_AU-_-%2Bibm %2Bstatistical %2Bpackage %2Bfor %2Bsocial %2Bsciences_b&cm_mmca1=000000OA&cm_mmca2=10000380&cm_mmca7=9072215&cm_mmca8=kwd-52095.

VR evaluation questions regarding tool usability[113] and presence[114]. The results of this second part have been presented in a previous paper.[115] The model interaction and design perception (12 questions), the participants' previous skills and experiences on the workshop topics (3 questions), and the user comments are presented and discussed in this section.

### 4.1.3 The Results and Discussion

This section examines the tool from the architectural point of view in terms of design perception and model interaction. For supporting questionnaire results, user comments were also included in this section.

The overall results for the design perception section were obtained as a mean value (MV) of 3.69/5.0 with a 1.12 standard deviation (ST.D.). Since the neutral level for the questionnaire was 3.0/5.0, it can be deduced that the findings verify the claims of Pertaub et al.[116] This result implies that the design perception of the environment was satisfactory. HoloArch allows users to see their designs in multiple scales with the aid of the MR appliance and the holograms and to act as they do in the physical reality. One participant stated that while experiencing HoloArch, he/she had difficulties from time to time in distinguishing the physical and virtual spaces as the boundaries were blurred between the two realms. Another participant noted that MR gave him/her the opportunity to become fully aware of what was happening around

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[113] John Brooke, "SUS - A Quick and Dirty Usability Scale," *Usability Evaluation in Industry* 189 (1996): 4–7, https://doi.org/10.1002/hbm.20701.
[114] Bob G. Witmer and Michael J. Singer, "Measuring Presence in Virtual Environments: A Presence Questionnaire," *Presence: Teleoperators and Virtual Environments* 7, no. 3 (1998): 225–40, https://doi.org/10.1162/105474698565686.
[115] Ibid, 17.
[116] David Paul Pertaub, Mel Slater, and Chris Barker, "An Experiment on Public Speaking Anxiety in Response to Three Different Types of Virtual Audience," *Presence: Teleoperators and Virtual Environments* 11, no. 1 (2002): 68–78, https://doi.org/10.1162/105474602317343668.

himself as he/she could perceive both the physical and virtual environment simultaneously.

Table 4.1. *Results for the questionnaires*

| | | | |
|---|---|---|---|
| 7 Questions | **Interaction in MR** | **MEAN** | **ST.D. DEV.** |
| | My interaction with the environment and the objects felt natural. | 3.22 | ±0.78 |
| | The visual aspects of the environment helped me to feel involved. | 3.67 | ±1.24 |
| | My sense of objects in the environment was compelling. | 3.56 | ±0.95 |
| | My experiences in the immersive environment were consistent with my real-world experiences. | 3.56 | ±0.49 |
| | I was able to examine objects closely. | 4.00 | ±0.94 |
| | I felt involved in the immersive environment because the model interaction was responsive. | 4.22 | ±0.78 |
| | I lost track of time while I was interacting within the immersive environment. | 4.11 | ±0.73 |
| | **Overall Success** | **3.76** | **±0.33** |
| 5 Questions | **Design Perception** | **MEAN** | **ST.D. DEV.** |
| | My perception of the building geometry was successful. | 3.33 | 1.25 |
| | My exploration was successful. | 4.00 | 0.94 |
| | I found the visualization of the BIM data successful. | 3.56 | 1.34 |
| | The visualization of the daylighting results was successful. | 3.89 | 0.99 |
| | I could associate the building design with the simulation results. | 3.67 | 1.05 |
| | **Overall Success** | **3.69** | **±0.23** |
| 3 Questions | **Skills and Experiences** | **MEAN** | **ST.D. DEV.** |
| | What were previous skills with Revit? | 1.67 | 1.05 |
| | What was the previous experience with daylighting simulations? | 3.33 | 0.94 |
| | What was the previous experience with immersive environments? | 3.00 | 1.25 |
| | **Overall Success** | **2.67** | **±0.72** |

However, when the section questions are examined separately, the perception of the building geometry received lower scores compared with the other questions in the section, with MV of 3.33/5.0 with the highest ST.D. value. A possible reason is identified as the physical qualities of the room that the workshop was conducted. Since the workshop was performed during day time, exposure to daylighting could have affected the visibility of the holograms. One participant added that he/she finds it difficult to perceive visual holograms due to their high translucency. Therefore, it is possible to suggest that dark rooms could offer a more suitable environment to experiment with MR environments in order to eliminate translucency problems. Another reason for this problem could be the visual conflict between the real objects and the holograms. Another issue addressed by the participants was related to understanding the 1:1 scale in MR. HoloLens has a limited field of vision. When users opt for bigger scales, the model geometry cannot fit in the boundaries of the display. This problem might have hindered the visual perception of the complete geometry. In this regard, one participant said that he/she had recurring problems about the field of view and it affected his/her comprehension of the model.

The absence of the materials in the model is identified as a potential challenge against visual perception. This was a conscious decision of the development team, due to the anticipated difficulties on the combined visualization of colorful daylighting simulations and materials. A visual overlap could lead to visual overload for the users. Therefore, the material textures were eliminated to be able to highlight the simulation results visually. Positively, this distinction between the model and analyses led to positive comments in the daylighting visualization section of the questionnaire that is scored as 3.89/5.0.

As widely mentioned in the existing literature[117], 3D visualization offers a better understanding of complex simulation results. In our case, similar results could be inferred. HoloArch's daylighting visualization capabilities were evaluated as the most prominent feature by a participant. In addition, the association of simulation results with the building geometry was found successful, with the MV of 3.67/5.0. The color-coding representing the level of the daylighting was appreciated by one of the participants as it offered instant identification of the problematic areas in the building. These comments imply that HoloArch's visualization methods are found

[117] Ibid, 11-43.

easy to process. The tool might have the potential to be used in the future as a serious game, towards the training of the users for complex daylighting simulations. In contrast, a participant pointed out the lack of simultaneous simulation updates while the objects -such as trees or shading elements in front of the façade openings are being moved. In the current version of HoloArch, daylighting analyses are conducted on Revit and this process is only unidirectional. Further studies on the simultaneous bidirectional workflow are needed to understand better how geometry editing affects the daylighting simulations. On the other hand, the visualization of the BIM data was found satisfactory according to the participants. However, the results were lower than the predictions with an MV score of 3.56/5.0 with ST.D. 1.34. Even though the results were higher than the neutral level, improvements in the visualization of BIM data is required. For this purpose, a hierarchical categorization can be implemented for receiving higher results in the further testing of HoloArch.

The overall results for the interaction section were MV of 3.76/5.0 with an ST.D. of 0.33. The results were satisfactory for the model interaction in MR. In HoloArch, users can explore their models by walking around and by getting closer to them. Users can select the objects that they want to move and relocate them in order to improve their daylighting design. One participant stated that using HoloArch with HoloLens gave him/her the opportunity to see the outside actions; therefore, he/she did not bump into physical objects. On the other hand, even the overall score was acceptable; some participants commented on the limitations related to the motion tracking and the gesture recognition during both the testing and the evaluation sections. In addition, the interaction method was not found natural enough as it had the lowest score among the other results in the section. According to Parsons et al.[118], IEs allow new ways to understand and to interact with architectural models and thus present a novel expanding field for architectural design thinking. Since MR is a

[118] Thomas D. Parsons et al., "Virtual School Environments for Neuropsychological Assessment and Training," 2018, 123–57, https://doi.org/10.1007/978-3-030-02631-8_8.

relatively new technology and its use is not familiar to many architects, participants might find it difficult to control the environment with their gestures. On the other hand, the results for the skills and experiences section were MV of 2.67/5.0 with 1.08 ST.D. The results regarding the low level of relevant experience (i.e., on Revit or daylighting simulations) might be another possible problem, which hinders the effective use of the developed tool. However, the overall results show that participants were still able to understand the aim of the tool.

In conclusion, the results of the questionnaire and the user comments verify the potentials of the tool. In particular, the tool's visualization capabilities were found more successful than the Revit environment in terms of visual perception, navigation through the model, and the visualization of integrated simulation data, as seen in the overall results illustrated in *Table 4.1*. Even though the participants faced several problems, the overall results were higher than the neutral level. This might be related to the participants' initial enthusiasm for experimenting with new technology, HoloLens. They showed a higher level of curiosity and engagement with the technology. Therefore, it is possible to claim that they might omit some of the limitations related to the HoloLens.

According to user feedback, HoloArch has the potentials in terms of daylighting analysis visualization, model interaction, increased visual perception. In contrast, HoloArch has limitations in terms of BIM data visualization and the absence of simultaneous daylighting analysis update. The number of participants at the workshop was limited due to the course capacity. Moreover, the allocated time for the workshop, which was 2.5 days, was insufficient to fully experiment with HoloArch considering the tool's complexity and the heavy workload of the workshop.

## 4.2 Immersive and Responsive Environments: Performative Architectural Design Workshop for HoloArch 2.0

HoloArch's second version (HoloArch 2.0) was adapted for both VR and MR environments. However, VR and MR were considerably different visualization technologies, as stated in the introduction section. Both of the environments were thought to offer different experiences for architects in terms of its model interaction and visual perception that play a significant role in architects' design activity. Therefore, HoloArch 2.0's behavior and performance in these environments were needed to be tested comparatively parallel to its prominent features for the tool's affordances. For that reason, another workshop was performed at the METU Faculty of Architecture with 21 participants. The workshop was organized by the METU Department of Architecture and Multimedia Informatics Program under the title Immersive and Responsive Environments: Performative Architectural Design.

### 4.2.1 Technologies

HTC Vive (VR) and Microsoft HoloLens (MR) were selected as primary head-mounted displays to provide different immersive experiences for HoloArch.

### 4.2.2 Participants

The participants were selected amongst architects and architecture students according to the answers they gave in the application questionnaire in *Table 4.2.*

Table 4.2. *Competence Questionnaire on the application form*

| Competence (3 questions)<br>(Answers from 1 to 7, 1 being most negative) | MV | ST.D. |
|---|---|---|
| What was the previous experience with Revit? | 4.62 | 1.56 |
| What was the previous experience with daylighting simulation? | 3.81 | 1.68 |
| What was the previous experience with immersive virtual environments (Virtual Reality, Mixed Reality, Augmented Reality)? | 4.19 | 2.08 |
| Overall Score of the Section (Mean Value) | 4.21 | |

The questionnaire shows participants' previous competences about the topics that HoloArch 2.0 covers. Even though the selection was performed by selecting the strong candidates who have a background in the relevant topics, the overall mean value (4.21/7.0) was not found satisfactory, and introductive tutorials and lectures were added to the program of the workshop to eliminate possible participant disorientations. The age distribution of the group was 23.88. *Figure 4.3* demonstrates the setup of the workshop environment and photos of the participants testing HoloArch.


*Figure 4.3.* A: A participant is using the HTC Vive to test HoloArch in VR, B: First-person view of HoloArch in MR, C: A participant is testing HoloArch tool with the Microsoft HoloLens in MR, D: HoloArch Logo, E: First-person view of the UI in MR, F: Participants are testing the tool in VR and MR during the workshop

### 4.2.3 Workshop Procedure

The first day was dedicated to lectures, tutorials, and hands-on exercises on sustainable conceptual design, daylighting design, and detailed BIM modeling. The participants were divided into five groups and were asked to design a home office building in different cities: Cairo, Egypt; Reykjavik, Iceland; Dublin, Ireland; Ankara, Turkey; Auckland, New Zealand. Each city presents various challenging daylighting conditions due to the different solar illumination they receive throughout a year. Participants started the design process by designing sustainable mass models in Autodesk FormIt. Then, the selected design alternatives were detailed in Autodesk Revit, and daylighting simulations were conducted in Autodesk Insight. The final designs were exported to HoloArch 2.0. Parallel to the first-day schedule, to prevent gadget related adaptation problems during the testing, HTC Vive and HoloLens orientations and tutorials were given to the participants. On the second day, all of the participants experienced their designs in VR and MR environments. One of the designs of the groups was selected as a case project for HoloArch 2.0. The Participants used HoloArch 2.0 to evaluate daylighting conditions of the selected building, to edit architectural elements, landscape and space planning of the design, and to navigate inside the design.

### 4.2.4 Data Collection and Analysis

The data collection was performed with both questionnaires and open-ended questions at the end of the workshop. Descriptive statistical analysis was performed for the questionnaires, and an ad-hoc method was used for the categorization of the open-ended questions.

#### 4.2.4.1 Questionnaires

For the qualitative evaluation of the tool, widely used System Usability Scale (SUS), Presence Questionnaire (PQ), and Technology Acceptance Model (TAM) questionnaires were adopted and distributed to the participants. The questionnaires were descriptively analyzed by using IBM SPSS. The total mean values were presented for each questionnaire for two different IE in the following section. Subsection based evaluation was omitted since the tool has various missing features. A brief explanation for the questionnaires as follows:

**PQ:** The effectiveness of IE has often been linked to the sense of presence reported by users of IE. Presence often is defined as a “sense of being there” in situations where a user felt in another environment. The questionnaire was first developed by

Witmer et al. in 1998[119], and it has various subsections, but only some of them included in the framework. The used items (19 questions) in the questionnaires can be seen in *Appendix A*.

**TAM:** TAM is a methodology that aims to unearth the potential acceptance, rejection, and usability of new technology. The methodology was introduced by Davis[120] , and it is widely used in the literature. Tam consists of different subsections, but only some of them included in the evaluation of HoloArch 2.0. The used items (13 questions) in the questionnaires can be seen in *Appendix B.*

**SUS:** System Usability Scale consists of 10 questions, with 5 response options from “strongly agree” to “strongly disagree”. The scale is become an industry standard and cited more than 8000 articles in the literature. The scale is suitable even with small sample sizes, and it provides quick, reliable results. The scale was developed by John Brooke in 1986.[121] The used items in the questionnaires can be seen in *Appendix C*.

#### 4.2.4.2 Open-ended Questions

Open-ended questions were found appropriate to learn unexpected and significant experiences from the participants. A similar technique on open-ended questions from Symoneaux et al.[122] was followed for the data acquisition method. The participants were asked to express their opinions on the potentials, limitations of HoloArch 2.0, and their suggestions on the tool’s improvement. In specific, the evaluation of the main tool functionalities such as multi-modal model visualization (integrated

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[119] Ibid, 114.
[120] Fred D. Davis, “Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology,” *MIS Quarterly: Management Information Systems*, 1989, https://doi.org/10.2307/249008.
[121] Ibid, 113.
[122] Amparo Tárrega and Paula Tarancón, “Free-Choice Profile Combined with Repertory Grid Method,” in *Novel Techniques in Sensory Characterization and Consumer Profiling*, 2014, 157–74, https://doi.org/10.1201/b16853.

visualization for BIM data and BIM geometry), daylighting simulation, performative design development was placed into focus in the data analyses. In addition, a comparative evaluation based on their experiences for visual perception and model interaction between MR and VR environments was made. The selected open-ended questions can be seen in *Table 4.3*.

Table 4.3. *Open-ended questions asked during data collection*

| |
|---|
| What are the main potentials of the current system? Please explain. |
| What are the main limitations of the current system? Please explain. |
| Which additional functionalities will be useful to improve the system? Please explain. |
| What are your suggestions for us to improve the model interaction for two different environments? Please explain comparatively. |
| What are your suggestions for us to improve the visual perception of two different environments? Please explain comparatively. |
| Which platform do you think is more effective and appropriate in visual perception for HoloArch? Why? Please explain comparatively. |
| Which platform do you think is more effective and appropriate in model interaction for HoloArch? Why? Please explain comparatively. |

The participants' responses to the open-ended questions were classified according to the questions for handling the vast amount of data. An ad-hoc approach was followed when categorizing the users' feedback. According to the collected data, the feedback concentrated on two different themes: (1) HoloArch 2.0's system evaluation and (2) comparative evaluation of visual perception and model interaction differences between mixed and virtual reality. The emerged themes were examined in detail in the results and discussion section of the second workshop.

### 4.2.5 Results and Discussion: Questionnaires

As a result of the evaluation of the questionnaires, surprisingly Microsoft HoloLens scored lower than HTC Vive in all the types. As HoloLens was a newer technology, it was thought that the participants would find it more preferable. In Tam questionnaires, while HoloLens had an MV score of 6.83/10.0 and HTC Vive had an MV score of 7.51/10.0. This can be explained that the participants might have had adaptation problems or found MR technology as strange. Since there is a correlation between the results, low usability problems, the low field of view, or adaptation to MR technology, effected the emergence of these results. In conclusion, HTC Vive has appeared as a more preferable and natural environment for HoloArch 2.0. However, the results were not found sufficient enough for both of the IE. These results have shown that HoloArch 2.0 requires additional enhancements to meet specific quality qualifications in terms of usability, sense of presence, and adaptation. The results can be seen in *Table 4.4.*

Table 4.4. *Questionnaire Results*

| | TAM (1-10) | SUS (1-100) | PQ (1-7) |
|---|---|---|---|
| Microsoft HoloLens | 6.83 | 64.4 | 4.64 |
| HTC Vive | 7.51 | 77.4 | 5.07 |

### 4.2.6 Results and Discussion: Open-Ended Questions

In this section, participants' feedback was presented and discussed under two categories: HoloArch 2.0's affordance for the architects and MR-VR comparison in terms of visual perception and model interaction.

#### 4.2.6.1 Tool Affordance

Participant feedback was classified according to the mentioned topic's frequencies. One of the objectives of the project was to develop an integrated, immersive tool for BIM users. HoloArch enables performative architectural design guided by the daylighting simulations, exploration, interaction, and visualization. HoloArch 2.0's most significant feature was identified as the combined 3d visualization of the daylighting analysis results with the building geometry (*Figure 4.4*).

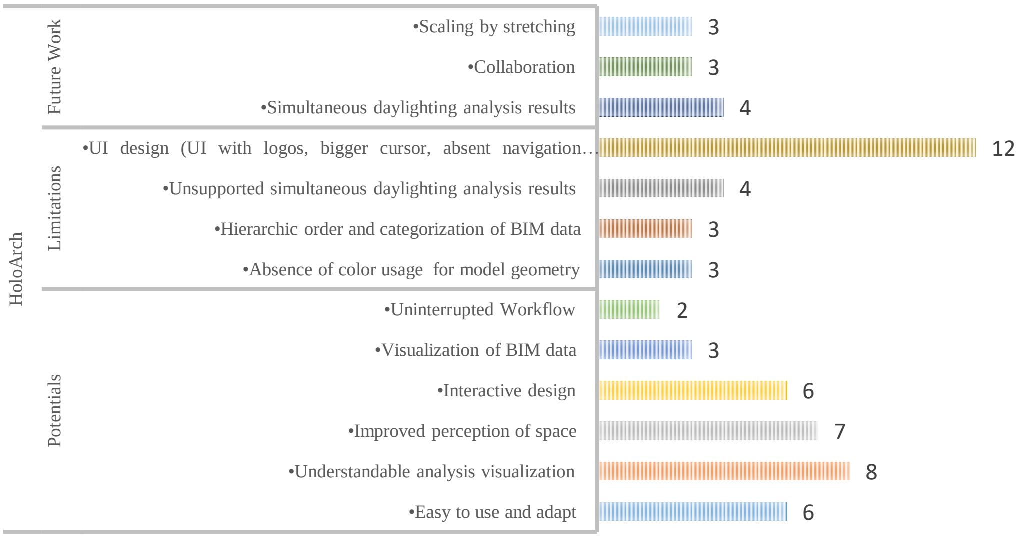


*Figure 4.4.* Categorization of the user feedback in tool affordance

One participant (P5) stated that design development was taken place primarily from the visualized simulation results that guided performative design editing activities. The example the participant gave was the addition of solar control devices based on the identification of daylighting problems in the architectural model. Three other participants compared HoloArch 2.0 with the 2D Revit environment and emphasized its ease of understanding. As widely mentioned in the existing literature[123], 3D visualization offers a better understanding in terms of complex simulation results. On the other hand, four participants addressed the lack of simultaneous updates of the daylighting analysis while they were editing their designs in HoloArch 2.0. In the current version of HoloArch, daylighting analysis is conducted on the Revit, and it is only unidirectional. Further studies about simultaneous bidirectional workflow

[123] Luisa Caldas and Mohammad Keshavarzi, "Design Immersion and Virtual Presence," *Technology Architecture and Design*, 2019, https://doi.org/10.1080/24751448.2019.1640544; Robert Stone et al., "The Virtual Scylla: An Exploration of 'Serious Games', Artificial Life and Simulation Complexity," *Virtual Reality* 13, no. 1 (2009): 13–25, https://doi.org/10.1007/s10055-008-0111-0; Louise H. Kellogg et al., "Interactive Visualization to Advance Earthquake Simulation," *Pure and Applied Geophysics* 165, no. 3–4 (2008): 621–33, https://doi.org/10.1007/s00024-008-0317-9.

are needed to understand better how geometry editing affects the daylighting simulations for the users.

HoloArch allows users to experience their models interactively. It enables to scale models in multiple options, to select and display building elements' properties individually. Another objective of this study to understand whether HoloArch 2.0 has a positive impact on architects' visual perception; seven participants mentioned improved design perception with the help of the tool. Since HoloArch 2.0 is an immersive application, it offers more advanced quality over orthographic architectural styles that architects accustomed to. Designing on a 1:1 scale was not typical for the architects. P19 stated that:

> "Using the tool in 1:1 scale was not possible in many conventional computer-displayed tools, but HoloArch [2.0] offers unique experiences in this matter."

P13 noted that:

> "HoloArch [2.0] allows an experience which is close to physical reality so that the designer could experience his/her design on a 1:1 scale."

These opinions imply similar results from the study of Parsons et al.[124] that suggests IE allowed new ways to understand architectural models and to expand architectural design thinking. On the other hand, the visualization method for building geometry received negative feedback from three participants. P15 pointed to the lack of materials in the application by saying that:

> "The visualization of the model was missing in terms of the materials; I would like to experience lifelike real-time rendering."

Despite the negative feedback, the lack of material information was a conscious decision of the development team, due to the anticipated difficulties on the simultaneous display results of colorful simulations and materials. A visual overlap could lead to visual overload for the users. The distinction of the model geometry and the simulation result was done by eliminating the material textures of the model.

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[124] Ibid, 118.

Positively, this distinction between the model and analysis led to positive comments in the daylighting visualization.

HoloArch 2.0 allows users to edit their BIM models according to understandable 3D analysis and to turn back the edited geometry in Revit without any data loss. This novel approach in performative architecture received positive comments. Interactive design capabilities of the tool were the third most pronounced potential of the tool, with six mentions along with the tool's easy to use and adapt nature. One participant (P11) claimed the tool was easy to adapt that even non-technical users could use it. These findings imply that HoloArch 2.0 holds the potential to ease hard to predict intricate daylighting design in architecture, and tools like HoloArch 2.0 could act as a learning environment for the education of architects.

On the other hand, multi-modal (BIM data and BIM geometry integrated) visualization did not get the expected outcome from the participants. In this issue, P7 and P21 emphasized the significance of proper hierarchic categorization in the visualization of the BIM data, and they stated the current version was not satisfactory for them. The reason for that could be related to the UI of the tool since semantic and geometric data visualization requires a robust UI design.[125] Based on the negative feedback, more studies on the improvement of the visualization of BIM data can be performed for HoloArch. Other UI related flaws of the system can be summarized as; absence of the navigation commends such as undo, delete and copy, *"ugly"* UI, and small cursor. It is known that the copy command is not possible for a reversible workflow to Revit since new elements can only be created by Revit inherently. However, the other suggestions placed into focus for the upcoming version of the HoloArch 2.0.

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[125] Weiyuan Liu, "Natural User Interface - Next Mainstream Product User Interface," in *2010 IEEE 11th International Conference on Computer-Aided Industrial Design and Conceptual Design, CAID and CD'2010*, vol. 1, 2010, 203–5, https://doi.org/10.1109/CAIDCD.2010.5681374.

#### 4.2.6.2 Comparative Study on Visual Perception and Model Interaction: VR and MR

Another aim of this study to explore possible visual perception and model interaction differences between two distinct immersive experiences. Regarding the users' comparison between VR, MR and computer display, while 10 out of 21 selected VR with HTC Vive, 9 out of 21 selected MR with HoloLens, two participants were reluctant to decide which technology is better and none of the participants selected computer display *(Figure 4.5*). From the figure, it can be seen that by far the highest demand is on VR.


*Figure 4.5*. The Participants' immersive environment preferences

##### 4.2.6.2.1 **Visual Perception Comparison**

IE is proven to improve the awareness of 3D models by increasing visual perception[126]. It was thought that the differences in technologies could affect architects' visual perception while they are using HoloArch. As expected, notable differentiations were spotted. Participants were asked: "Which platform do you think is more effective and appropriate in visual perception for HoloArch?". Consistent with the research from Birt et al.[127] , the answers pointed out that the majority of the

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[126] Ibid, 116.
[127] James Birt, Patricia Manyuru, and Jonathan Nelson, "Using Virtual and Augmented Reality to Study Architectural Lighting," no. 2015 (2017): 1–5.

participants preferred to use VR rather than MR for a more effective visual perception experience. However, this result was not anticipated, since MR was relatively newer and more advanced technology compared to VR. When the reason was asked, six participants said that to MR environment distracted themselves and it was not easy for them to perceive models. They also stated that surrounding physical objects and the translucent holograms frequently conflicted in MR. In contrast, P17 said:

> "I didn't get distracted from outside actions in VR. The environment and interaction were intuitive and easy."

The reason for that might be related to the high exposure of the room since the workshop was performed in the day time. The findings may imply that dark rooms could be more suitable for MR environments in order to eliminate visual conflicts.

During the testing, participants scaled their models to multiple ratios, such as 1:1 and 1:200. Seven participants indicated the problems they experienced with the 1:1 scale models in MR. According to them, it was hard to describe where they are, what they are looking at inside the model because there was a limited field of view on the MR display. In this issue, six participants suggested that MR tools were more suitable for smaller scales, such as 1:100 and 1:200. According to these, it can be inferred that as long as the holograms are inside the field of view of MR gadgets, they are more understandable and perceivable by the users. In contrast, some of the participants found MR was more successful for perception. They indicated that in MR, physical objects and virtual objects could be perceived together, and even cyber objects felt as they belonged in the physical reality. These findings confirm the results of prior studies of Lee et al.[128] However, in this study, VR environments found more successful in terms of visual perception by the architects.

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[128] Gun A. Lee et al., "CityViewAR: A Mobile Outdoor AR Application for City Visualization," in *11th IEEE International Symposium on Mixed and Augmented Reality 2012 - Arts, Media, and Humanities Papers, ISMAR-AMH 2012*, 2012, https://doi.org/10.1109/ISMAR-AMH.2012.6483989.

#### 4.2.6.2.2 **Model Interaction Comparison**

Another aim of this study was to understand the differences in model interaction capabilities of two differently working IE. VR gadgets such as HTC Vive have two wireless controllers that allow users to navigate, control, and interact within the cyber world. MR gadgets such as HoloLens, are controlled by the predefined user gestures recognized with motion-tracking cameras. It was thought in the beginning that the differences in control mechanisms could affect users' model interaction capabilities while they are using HoloArch. Thus participants were asked, *"Which platform do you think is more effective and appropriate in model interaction for HoloArch?"*. According to the categorization of the feedback, twelve participants selected VR as their first choice. However, minor differences between participant numbers pose challenges in making certain deductions. This result could be caused by several issues. One of the reasons could be explained with gesture recognition and hand tracking problems during the HoloLens experience. 4 out of 21 complained that the MR device did not respond appropriately to their gestures. It can be inferred that MR devices are relatively new technology and need further development in tracking issues. Another one could be related to the UI and the model confliction in MR; 5 out of 21 mentioned that when they tried to control the menu closer to their models, it became hard to interact with and reach UI. They added that model interaction was hindered because of the overlap problem. UI design in MR devices is a complex issue and needs significant attention; this deduction was also mentioned in the previous studies.[129] Another issue could be the different display principles of the environments because MR uses translucent holograms, and VR uses led pixel system

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[129] David Lindlbauer, Anna Maria Feit, and Otmar Hilliges, "Context-Aware Online Adaptation of Mixed Reality Interfaces," in *UIST 2019 - Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (Association for Computing Machinery, Inc, 2019), 147–60, https://doi.org/10.1145/3332165.3347945; Sunwook Kim, Maury A. Nussbaum, and Joseph L. Gabbard, "Influences of Augmented Reality Head-Worn Display Type and User Interface Design on Performance and Usability in Simulated Warehouse Order Picking," *Applied Ergonomics* 74 (January 1, 2019): 186–93, https://doi.org/10.1016/j.apergo.2018.08.026.

to display virtual elements. The visibility of the virtual objects' impact on the model interaction was mentioned by five participants. P11 said that translucently displayed objects in MR were not visible enough to see his/her modifications to the architectural model. In comparison, he/she found VR more responsive and livelier. Similar to the implication made on the visual perception section, darker rooms can augment the visibility of the holograms due to achieve better model interaction in MR.

Even though MR had low scores compared to VR, it was preferred by nine participants. On the other hand, when comments were examined, it was found that more than 10 out of 21 people pointed out how MR was hard for them to control and interact. Despite controlling and interacting, were found hard, why 9 out of 21 participants selected MR as their first choice? This might be related to the participants' initial excitement when they were using expensive HoloLens. They showed a higher level of curiosity and engagement to newer technology, so they might omit the limitations of the MR. Another reason for the selection might be the affordance potentials of the MR over VR. In MR, users could anchor their models in the physical world and could explore their models by walking inside or around their buildings. However, in VR, due to the cords and fixity problem, users had to experience HoloArch 2.0, whether in sitting or standing position and for the exploration of the model, users had to use controllers to walk. 7 out of 21 agreed that MR offered a more interactive environment because it's model interaction capabilities were more close to real life. It can be inferred that users' mobility capabilities in IE directly affect model interaction.

In sum, HoloArch 2.0 has potentials in terms of daylighting analysis visualization, interactive performative design, easy adaptation, and usability. In contrast, HoloArch 2.0 has limitations in terms of unsatisfactory BIM data visualization, absence of simultaneous daylighting analysis update, and UI design. Apart from that, the majority of the participants in both of the comparative studies (model interaction, visual perception) found that the VR environment was more suitable for tools similar to HoloArch 2.0.

# CHAPTER 5

# THE USER STUDY

## 5.1 Aims and Objectives

Different from the other versions, HoloArch 3.0 has all the required qualifications as appointed at the beginning of this study. With HoloArch 3.0, users can reach and use all the possible designated actions without the negative effect of the missing features that were incomplete in the earlier versions. In addition to completeness of the required features, the tool's usability aspects, visual aesthetics, and interaction design were also improved in this version in light of the feedback collected in earlier workshops, as mentioned in Chapter 4. Similar to the earlier versions, the most advanced and upgraded version of HoloArch (HoloArch 3.0), was needed to be tested, evaluated, and validated with the conduction of a new user study. Besides, this study was anticipated to reveal HoloArch's true capabilities, limitations, and contributions to the field of architecture.

In this manner, another user study designed according to achieve particular objectives. These are as follows:

- To test newly added design actions and to assess their performance on users' performative design activity,
- To understand the influence of the newly designed UI, and the updated visual features to user navigation, user satisfaction, and usability of the tool,
- To clarify, to what extent HoloArch 3.0 complete with all the pre-concerted features, affects the users' design performance in immersive environments,

- To reveal the observable differences in system usability, presence, and technology acceptance questionnaire performance of the tool in comparison with HoloArch 2.0,
- To test whether the users can perform design actions that can influence on the daylighting performance of the case building via HoloArch, or not,
- To find out HoloArch's strengths, weaknesses, opportunities, and threats with SWOT analysis,
- To collect data via observations, in-depth interviews, and questionnaires that can contribute to constituting a data pool for answering this thesis' research questions.

## 5.2 Tools and Technologies

The feedback obtained from the second user study's participants revealed that the virtual reality tool HTC Vive tends to be preferable by the participants. The majority of the comparative questionnaire items were answered in favor of virtual reality with HTC Vive against mixed reality with Microsoft HoloLens. According to feedback HTC Vive was found more suitable in terms of its use, design perception, model interaction, navigation, and its performance on design actions in immersive environments. The Microsoft HoloLens was launched only in developer edition and for enterprise users as an experimental study. HoloLens was not introduced to the customer market because of the tools' bulky headset and a limited field of view. The usability of Microsoft HoloLens was not found useful enough, and several academic papers were pointed out by mentioning its flaws.[130] In February 2019, Microsoft

[130] Nikolas Chaconas and Tobias Hollerer, "An Evaluation of Bimanual Gestures on the Microsoft HoloLens," in *25th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2018 - Proceedings*, 2018, 33–40, https://doi.org/10.1109/VR.2018.8446320; Donghao Ren et al., "Evaluating Wide-Field-of-View Augmented Reality with Mixed Reality Simulation," in *Proceedings - IEEE Virtual Reality*, vol. 2016-July, 2016, 93–102,

decided to pull HoloLens out of the market and introduced HoloLens 2. Therefore, according to the workshop feedback and Microsoft's intervention to HoloLens, the user study was decided to conduct only with HTC Vive with virtual reality.

## 5.3 Participants

The user study was designed in light of the abovementioned objectives. The study was decided to be conducted with the participants who also attended to Immersive and Responsive Environments workshop, where HoloArch 2.0 was tested in November 2018. In this way, possible incompetency problems in the use of HoloArch was eliminated because all of the prior participants were taught in the related subjects such as immersive environments, daylighting design, building information modeling. Since they had experience in immersive environments, and they had knowledge about how to use HoloArch with HTC Vive, the prior participants from METU were selected one more time. In order to save time, taught courses and modeling process was discarded out of the user study program.

The reliability of a user study is related to the population of the experiment subjects.[131] In the previous workshops, the sample size varied between nine to twenty-two participants. Working with a comparatively large sample size was convenient in detecting the most critical and prior interventions for the new HoloArch. According to the questionnaire outcomes, significant updates and additional features were added to the development agenda for HoloArch 3.0.

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https://doi.org/10.1109/VR.2016.7504692; Edouard Auvinet et al., "O100: Validation of the Precision of the Microsoft HoloLens Augmented Reality Headset Head and Hand Motion Measurement," *Gait & Posture* 57 (2017): 175–76, https://doi.org/10.1016/j.gaitpost.2017.06.353; Wei Wangm et al., "Holo3DGIS: Leveraging Microsoft Hololens in 3d Geographic Information," *ISPRS International Journal of Geo-Information* 7, no. 2 (February 9, 2018): 60, https://doi.org/10.3390/ijgi7020060.

[131] Peter M. Steiner, Christiane Atzmüller, and Dan Su, "Designing Valid and Reliable Vignette Experiments for Survey Research: A Case Study on the Fair Gender Income Gap," *Journal of Methods and Measurement in the Social Sciences* 7, no. 2 (2017): 52–94, https://doi.org/10.2458/v7i2.20321.

According to Virzi[132], testing with five people might be enough to construct a representative sample size to expose the problems, limitations, and potential of the tested product.

According to *Figure 5.1*, 85% of the problems found in usability studies tend to emerge with the initial five participants. It can be inferred that user studies conducted with elaborate sample sizes might be lost of time and sources for the researchers who look for immediate and effective outcomes. Problems and insights of tested products pointed by initial participants repeatedly recur with each additional participant. Besides, inferences taken out of user studies become nonyielding in terms of learning outcomes compared to the dedication and time devoted by researchers.

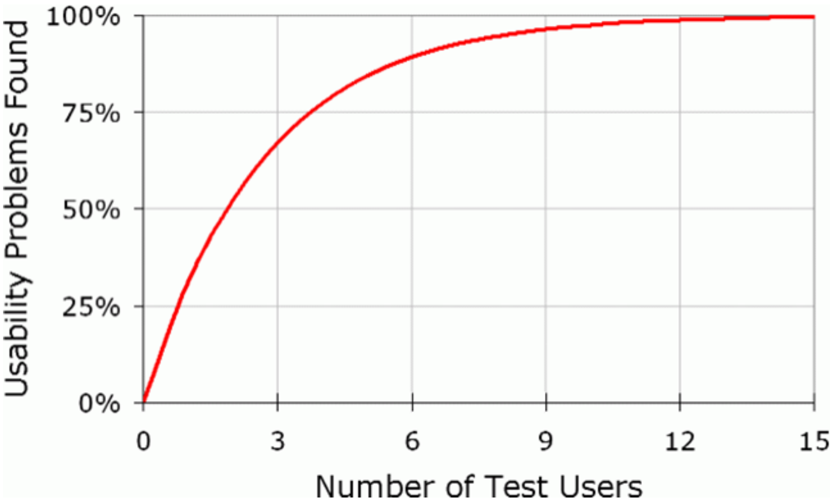


*Figure 5.1.* The correlation between user problems found in user studies and their sample size[133]

HoloArch 3.0 was designed as a case study to meet this thesis' requirements that aim to answer specific research questions. For the abovementioned reasons, the user

[132] R. A. Virzi, "Refining the Test Phase of Usability Evaluation: How Many Subjects Is Enough?," *Human Factors*, vol. 34, 1992, https://doi.org/10.1177/001872089203400407.
[133] Jakob Nielsen and Thomas K. Landauer, "Mathematical Model of the Finding of Usability Problems," in *Conference on Human Factors in Computing Systems - Proceedings*, INTERCHI '93 (Amsterdam, The Netherlands, The Netherlands: IOS Press, 1993), 206–13, https://doi.org/10.1145/169059.169166.

study was decided to be performed with five former participants. All of the selected participants were graduate students who have prior knowledge of the related subjects. The manageable group size made possible a more in-depth examination of the tool in a prompted and effective way. Different from the other user studies, the manageable sample size of the final study, allowed the participants to spend more time in the environment and to take their time to test the tool thoroughly.

### 5.4 Procedure of the Final User Study

The total duration of the study was determined to 2 hours per participant, including 15 minutes break. However, some of the participants stated they required more time to finish their designs, so up to 15 minutes extension was also provided in some cases. The study had seven main stages that were distributed as determined time intervals in the duration of the study. During the user study, the procedure was followed, and its stages and their contents as follows:

**Introduction:** The first part of the study consists of the distribution of the consent forms, a brief recallment of the fundamental concepts of HoloArch, a brief explanation about the procedure, and practical information about the control of the environment and VR gadget.

**Protocol:** Before the participants initiate the design process, the tool's interface and its features will be introduced while they are wearing the VR gadget. In order to show participants how all the features of the application functioning, succinct instructions will be given before they begin the design process via HoloArch. Different instructions given to participants may affect the reliability results.[134] For the elimination of inconsistencies and differences in the instructions, a protocol is

[134] Jonathan Lazar, Jinjuan Heidi Feng, and Harry Hochheiser, *Research Methods in Human-Computer Interaction, Research Methods in Human-Computer Interaction*, 2017, https://doi.org/10.1016/b978-044481862-1/50075-3.

determined to be sure each participant will be informed in the same conditions. In that way, any systematic errors caused by procedural bias were tried to be prevented. It is planned that the participants will apply the dictated actions according to the comprehensively prepared instructions in the protocol document. Since the participants will be wearing the headset, all of the instructions will be readout. The protocol will allow the participants to explore and to learn how to control and use the system. The protocol has 14 steps and three types consisting of exploration, design, and workflow actions. The time spared for this stage is ten minutes. The steps of the protocol can be seen in *Table 5.1*.

Table 5.1. *The followed Instruction Protocol*

| | **Action Types** | **Instructions** |
|---|---|---|
| 1. | Exploration Action | Place UI to above the head |
| 2. | Exploration Action | Wander around the building by teleporting |
| 3. | Exploration Action | Activate wireframe view to see inside the building |
| 4. | Exploration Action | Go inside the building by hiding envelope |
| 5. | Exploration Action | Select any building elements and display its BIM data |
| 6. | Exploration Action | Scale building to 1/100, 1/2, 1,10 |
| 7. | Exploration Action | Turn on/off shadow rendering |
| 8. | Exploration Action | Visualize morning simulation data |
| 9. | Design Action | Change building orientation in bird-eye view |
| 10. | Design Action | Change width and height of any window |
| 11. | Design Action | Change material of any window |
| 12. | Design Action | Place shading element and change its rotation |
| 13. | Design Action | Place furniture and tree |
| 14. | Workflow Action | Apply changes |

**Design:** After the initial adaptation to the system, participants will be freed to do any actions they desire for 30 minutes. Since the participants will have adapted themselves to the system in the protocol stage, they performed design actions without the distraction caused by any further guidance. During the design phase, the actions of the designers are anticipated as follows; they will tend to interpret the daylight analysis of the building, and they will tend to edit the elements of the building in order to improve the daylighting efficiency of the design. After the participants finalized their design, they will apply all of the changes in the model in order to update the BIM model and daylighting analyses.

**Update of the Design**: The changes made in the case study building via HoloArch in prior stages, will be transferred to the BIM environment for re-conduction of the daylighting analyses via Autodesk Insight. The geometry will be updated automatically according to the changes made in the IE by using RF Tools' Revit Plug-in. Since Autodesk Insight is a cloud-based system, the conduction of the analyses takes time because of its queue-based priority working principle. For the queue related time elongations, 15 minutes are devoted to this stage.

**Comparison:** The fifth stage of the procedure is based on the comparison of the baseline and the participant's daylighting designs by synchronically switching between daylighting simulations' visualization in HoloArch. It is planned that participants will see the effect of their performative actions and their decisions' reflection on daylighting efficiency. In this way, the participants are anticipated to understand how their actions will shape the daylighting condition of the baseline design. This stage constitutes the final part of the immersive experience.

**Questionnaire:** A small break reducing possible motion sicknesses caused by the immersive experience is given between the comparison and questionnaire stage for the participants to recover themselves. For data collection matters, a questionnaire set including widely used TAM, PQ, SUS questionnaires is distributed to participants. Ten minutes are spared at this stage for the completion of the questionnaires.

**One to One Interview:** As the final stage of the procedure, 40 minutes in-depth one to one interview is designed to collect extensive feedback from the participants. The illustration of the procedure stages can be seen in *Figure 5.2*.

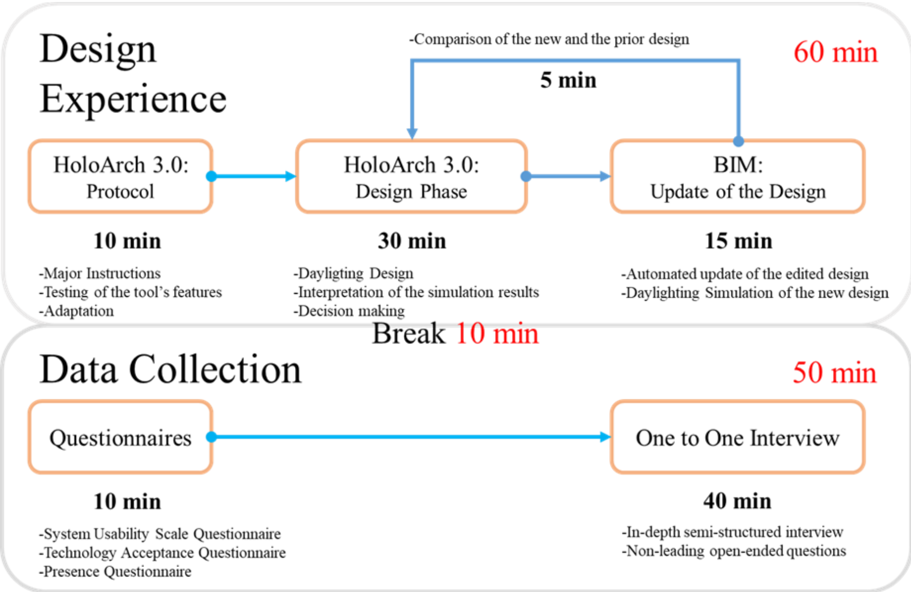


*Figure 5.2.* The structure of the final user study

## 5.5 Research Ethics

Before the beginning of the user study, mandatory consent form stated in the Turkish Presidency of the Council of Higher Education (YÖK)'s directive on scientific research and publication ethics[135], was submitted for the participants' review. The consent form consists of detailed and explicit information that covers a brief summary of the study's aims and objectives, the importance of participant's contributions, data collection methods, possession of their personal data, how their data will be used, what will be expected from them. The prepared consent form clearly states that the participants have the right to leave whenever they feel disturbed and uncomfortable during the immersive experience. In this way, they were also informed about the possible adverse effects of VR platforms, including nausea and motion sickness. The example of the consent form used in the previous METU

[135] "YÖK - English Ana Sayfa," accessed December 24, 2019, https://www.yok.gov.tr/en.

workshop can be seen in *Appendix D*. The consent form was reviewed by the five participants of the user study, and all of them confirmed the agreement.

## 5.6 The Case Study Project: Three Piece House by TRIAS

Different from the other workshops, a case study building was selected rather than the participant's own designs. In this way, the time spent on the modeling and designing steps was shifted to interviews and the immersive experience. As learned in the previous workshops, the participants' models sometimes cannot be suitable for them to experience the tool's features freely. For instance, in the previous METU workshop, a participant group designed a guitar-shaped building which has curvilinear surfaces that caused the occurrence of not well-fitted windows and non-functional spaces. These problems in the geometry challenged the participants to place shading elements to the sunken windows and to furnish small architectural spaces with items of furniture that could not be aligned to the walls. In order to prevent participant related complications, similar to other workshops, a case study home office building was selected and pre-modeled before the study. The visuals related to the case study building can be seen in *Figure 5.3, Figure 5.4, Figure 5.5.*

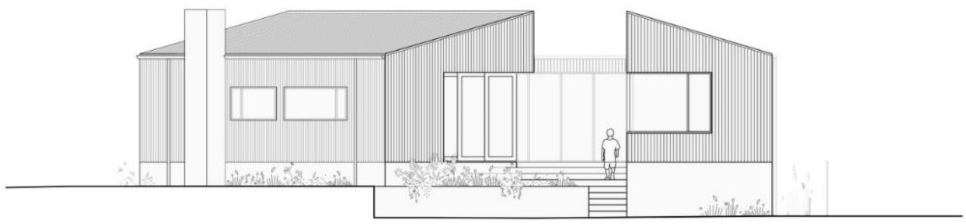

*Figure 5.3.* Elevation drawing of Three Piece House by TRIAS Studio[136]

[136] "TRIAS - Three Piece House," accessed December 24, 2019, https://www.trias.com.au/three-piece-house.

*Figure 5.4.* The Photos of Three Piece House by TRIAS Studio[137]

The building named Three Piece House by TRIAS studio has various windows in different sizes and offers plenty of spaces for the participants to navigate easefully. The house comprises of 114 m2 living quarter and 22 m2 separate office block and a big garden. The design holds two 2018 AIA NSW Architecture Awards for house and sustainability.[138]

[137] Ibid.
[138] Ibid.

*Figure 5.5.* The photorealistic rendered views of the BIM model of the case study building

## 5.7 Immersive Experience During the User Study

The user study was conducted as it was planned according to the procedure. The participants arrived at the appointed time, so no time shifts occurred between each user session. The user study was conducted in a meeting room at the METU's Faculty of Architecture, where has enough space for the participants to move and use their bodies freely. The study setup consisted of an HTC Vive, two computers (one for running HoloArch and for recording the virtual environment actions of the participants, and the other one for re-simulating the edited BIM models), a camera attached with a tripod underneath for recording the participant sessions, a voice recorder for recording the oral comments of the users both during their immersive experience and interview sessions.

In the user study, the participants were thought they might want to leave the session due to the discomfort problems and the long duration of the immersive experience. Contrary to expectations, the participants could manage to stay until the end of the immersive sessions. The only problematic part of the procedure was the conduction of the new daylighting simulations because of the queue elongation problems in Autodesk's cloud system; the participants had to wait for an additional ten minutes to get the simulation results. However, all of them expressed their appreciation for participating in the user study. The participant's photographs taken during their immersive experience can be seen in *Figure 5.6*, and their first-person point of view in the HoloArch can be seen in *Figure 5.7*.

*Figure 5.6.* Four of the participants working on their performative designs

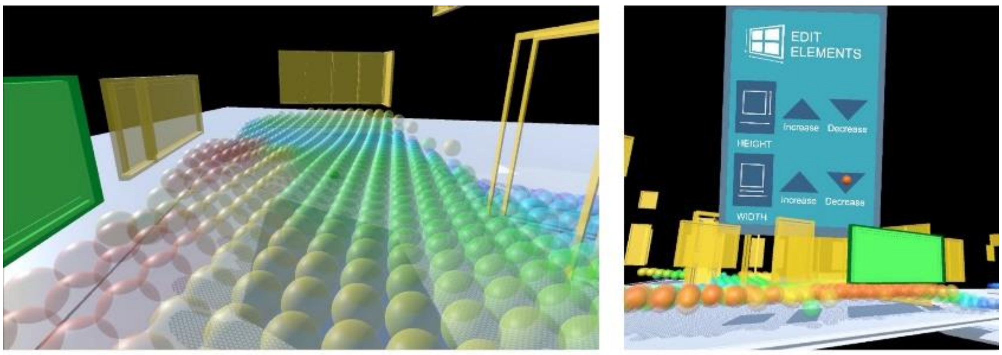


*Figure 5.7.* The Participants working on their performative designs via HoloArch

### 5.8 Data Collection Methods

Compared to the other workshops, the user study was conducted with only a few participants. The limited sample size in the study might jeopardize the credibility of the findings, and this was mentioned in several papers.[139] Therefore, in order to eliminate credibility related issues that might arise from the small sample size, the data collection methods in the study were expanded, and qualitative data gathering methods were also added to the questionnaire-oriented qualitative methods used in previous workshops. As a consequence, extensive data collection from the participants was determined as a mandatory goal of the study to evaluate the system and its outcomes in-depth. In order to increase the credibility of the study, a hybrid data collection method was developed and followed, comprising of both qualitative and quantitative methods. The hybrid approach used in data collection has similarities to Kitson et al., who used a similar approach in UX studies of a VR tool.[140] The collected data was used to understand how HoloArch can function in reality, to answer the research questions of the thesis, and to ascertain the potentials of immersive environments in performative design. After the immersive experience sessions of the participants, they were asked to participate in the data collection process.

#### 5.8.1 Quantitative Data Collection Method: Questionnaires

Similar to the previous METU workshop, a questionnaire set was prepared with TAM (fourteen questions), PQ (nineteen questions), SUS (ten questions)

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[139] Robert E Slavin and Dewi Smith, "Effects of Sample Size on Effect Size in Systematic Reviews in Education," *Annual Meetings of the Society for Research on Effective Education*, 2008, www.bestevidence.org; Jorge Faber and Lilian Martins Fonseca, "How Sample Size Influences Research Outcomes," *Dental Press Journal of Orthodontics* 19, no. 4 (July 1, 2014): 27–29, https://doi.org/10.1590/2176-9451.19.4.027-029.ebo.

[140] Alexandra Kitson et al., "Comparing Leaning-Based Motion Cueing Interfaces for Virtual Reality Locomotion," in *2017 IEEE Symposium on 3D User Interfaces, 3DUI 2017 - Proceedings*, 2017, 73–82, https://doi.org/10.1109/3DUI.2017.7893320.

questionnaires in order to understand HoloArch's updated features' contributions and reflections on two main categories covering the usability of HoloArch and the presence of the participants in the immersive environment. During both workshops and the user study, HoloArch continuously tested in terms of usability and its features. The prepared questionnaire set was identical to the previous METU workshop questionnaire's SUS, PQ, and TAM sections for HTC Vive. Asking the same questions to the same participants for different versions of HoloArch made it possible to compare these versions accurately. However, design perception, engagement, and affordance sections were discarded out in this user study's questionnaire set because these sections' outputs were planned to be collected during individual interviews for getting more feedback.

### 5.8.2 Qualitative Data Collection Method: Interviews and Observations

Since there was a limited sample size, data collection methods were supported by the integration of qualitative methods in the data collection parts. The user study's participant feedback was collected by using different technologies such as a voice recorder for recording the one to one interview sessions, a video camera for recording the participants' immersive experience session from physical world (*Figure 5.8)* and a screencast recording tool for recording the participants' first-person views during they were wearing the headset (*Figure 5.9*). The interview questions were asked in English, but the participants' responses were given in Turkish. By using their mother tongue, they felt more comfortable to share their ideas. The data collected during the immersive experiences of the participants were used to verify and understand the feedback given to the questionnaire and interview questions.

The one to one interviews were carried with the participants after the questionnaire session. The interviews were found useful to get a more in-depth understanding of the participants' feedback by ascertaining underlying thoughts and validating assumptions. During the interviews, the interviewer paid attention to ask broad, non-leading questions to the participants. This approach allowed the participants to give insights into the emergence of further follow-up questions.[141] The follow-up questions were employed for clarification and further expansion of the main questions' responses.[142]

*Figure 5.8.* Time frames from video recordings

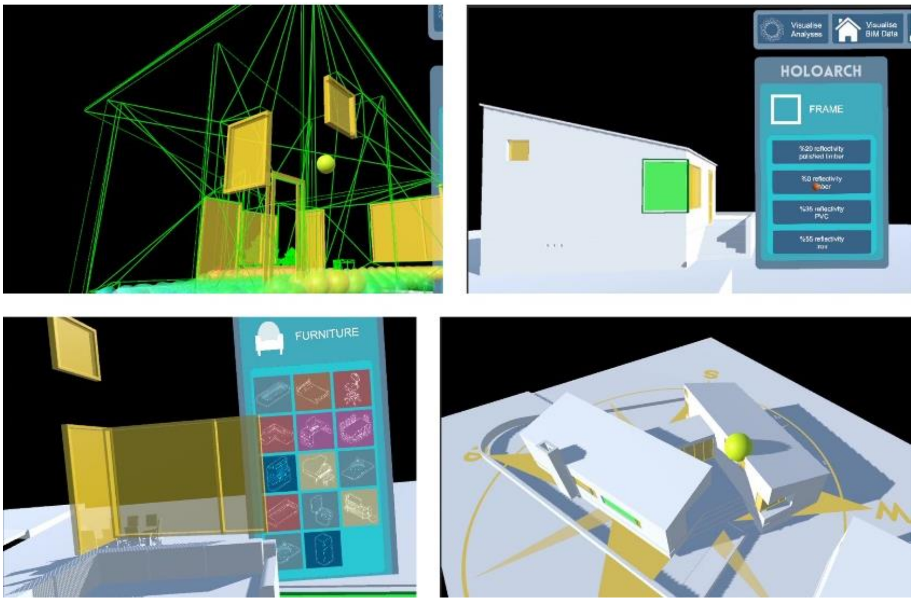


*Figure 5.9.* First-person view of the participants in the immersive environment

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[141] Herbert Rubin and Irene Rubin, "Preparing Follow-Up Questions," in *Qualitative Interviewing (2nd Ed.): The Art of Hearing Data*, 2012, https://doi.org/10.4135/9781452226651.n9.
[142] William C. Adams, "Conducting Semi-Structured Interviews," in *Handbook of Practical Program Evaluation: Fourth Edition*, 2015, 492–505, https://doi.org/10.1002/9781119171386.ch19.

The semi-structured interviews turned to a general conversation between the interviewer and the interviewees rather than a fully structured protocol. In this way, interviewees felt comfortable to discuss and share ideas with the interviewer. However, a few questions were prepared according to the thesis' research questions to prevent digression from the objectives of the study. The semi-structured interview questions can be seen in *Table 5.2*. During the interviews, the participants showed high enthusiasm to answer the questions and to debate relevant topics by giving a lot of examples from their prior experiences. As expected, the total duration of the interviews was taken approximately forty minutes for each participant.

Table 5.2. *Individual Interview Questions*

| **Individual Interview Questions** |
|---|
| 1. Compared with your previous experiences, how would you describe your experience with HoloArch? What did you like to do most? Why? |
| 2. What do you think the purpose of developing this tool can be? |
| 3. What sort of impacts did HoloArch have on you by combining different concepts? Could you please explain this in more detail? |
| 4. What kind of contributions has HoloArch made to your; design process / design perception / model interaction/ performative design? |
| 5. Compared to HoloArch 2.0, what are the eye-catching differences in this version? |
| 6. Have you felt any discomfort or usability problems during your experience? If you have, what sort of difficulties did you face during your experience? |
| 7. Could you please describe, what do you think about the visualization techniques (for analyses, geometry, BIM data) used in HoloArch? |
| 8. What are the most prominent strengths of HoloArch for you? Could you elaborately explain? |
| 9. What are the most noticeable flaws of HoloArch for you? Could you elaborately explain? |
| 10. Would you like to prefer using HoloArch in your professional projects if it would be a free-plug-in for Autodesk Revit? Why? |
| 11. What would you like to say about the future of immersive design environments? |

## 5.9 Data Analysis Methods

During the user study, different data collection methods were applied to get comprehensive feedback. The obtained feedback types were analyzed according to their nature in order to make inferences about the user study. The data analyses for both qualitative and quantitative methods were summarized in the diagram that can be seen in *Figure 5.10*.

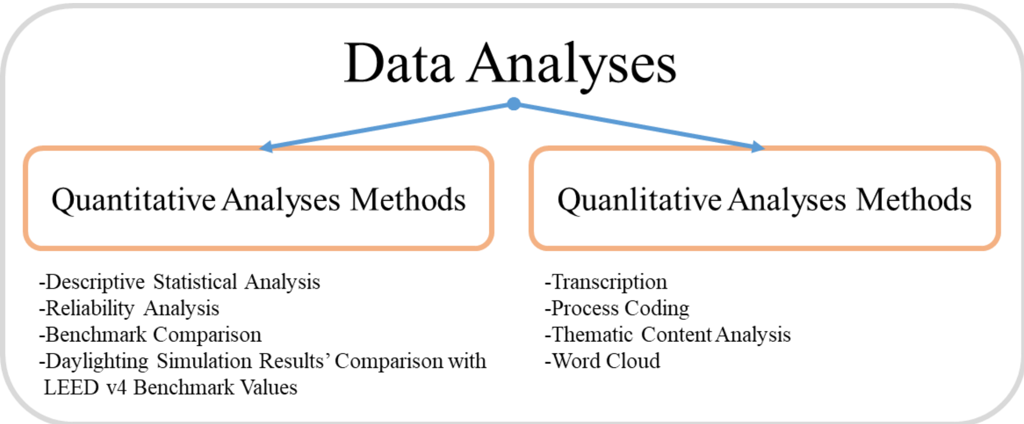


*Figure 5.10.* Data analysis' stages

### 5.9.1 Quantitative Data Analysis: Questionnaires

The questionnaires were collected after the user evaluation and were analyzed according to their recommended specific measurement methods. The subsections' averages, overall averages, and their standard deviations were calculated by descriptive analyses in IBM SPSS software. Since the applied questionnaire types in the study are frequently used in the literature, their own specific assessment methods adhered to the analysis process. In this way, the results became suitable for comparison with benchmark values in the literature. The method followed in the previous studies was applied in this user study as well.

Reliability analyses were conducted for each questionnaire, whether the internal consistency of the mean values is satisfactory or not by controlling the means' Cronbach Alpha (α) values. This method is commonly used to verify questionnaires consisted of multiple Likert questions.[143] Taber mentioned the recommended alpha values as:

> "… alpha values were described as excellent (0.93–0.94), strong (0.91–0.93), reliable (0.84–0.90), robust (0.81), fairly high (0.76–0.95), high (0.73–0.95), good (0.71–0.91), relatively high (0.70–0.77), slightly low (0.68), reasonable (0.67–0.87), adequate (0.64–0.85), moderate (0.61–0.65), satisfactory (0.58–0.97), acceptable (0.45–0.98), sufficient (0.45–0.96), not satisfactory (0.4–0.55) and low (0.11). "[144]

The reliability analyses were also conducted for each sub-sections of the questionnaires via IBM SPSS, and the outcomes were presented in the Qualitative Results section.

### 5.9.2 Quantitative Data Analysis: Comparative Analysis of the Daylighting Conditions

Along with the questionnaire outcomes, the daylighting analysis results of the edited BIM models were also analyzed. Since daylighting analysis results were already conducted during the user study and were presented visually to the participants in their HoloArch experience, there was no need to re-simulate the analyses again. It is essential to state that, during the conduction of the analyses, the temporary family categories were hidden (i.e., the moveable furniture pieces) to prevent their intervention to the daylighting analysis results. In the data analyses, numerical comparison of the daylighting calculations of each edited geometry was found useful

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[143] Jose M. Cortina, "What Is Coefficient Alpha? An Examination of Theory and Applications," *Journal of Applied Psychology* 78, no. 1 (1993): 98–104, https://doi.org/10.1037/0021-9010.78.1.98.
[144] Keith S. Taber, "The Use of Cronbach's Alpha When Developing and Reporting Research Instruments in Science Education," *Research in Science Education* 48, no. 6 (December 1, 2018): 1273–96, https://doi.org/10.1007/s11165-016-9602-2.

to understand whether the participants genuinely could improve the daylighting performance of the baseline BIM model or not. In other words, the results were controlled whether performative design actions could be engaged via HoloArch or not.

In HoloArch 3.0, LEED v4 EQ credit 7 option 2 was selected and used as the primary daylighting assessment analysis type. The simulation option was specified by U.S Green Building Council[145], and it works with point-in-time principles. The simulation option averages both autumnal and spring equinox illumination levels in specific points at particular spaces, and it grades calculated illumination values according to 300-3000 lux threshold levels. Along with the baseline model's as it is performance, the participants' edited models were compared with LEED's benchmark values, and the outcomes were presented in the Results section. According to LEED's benchmarking criteria, one point is given if the percentage of regularly occupied floor area's illumination is between 75% and 90% threshold; and two points are given if the threshold is 90% and above.[146]

### 5.9.3 Qualitative Data Analysis: Thematic Content Analysis

The recordings of the interviews were the primary data source for the qualitative analysis of the final user study. Each participants' voice recordings were transcribed verbatim and examined in conjunction with the observations, and the screencast, camera recordings of the participants' experiences. The total word count of the textual data emerged as 9804 words in total. After the transcription was completed, the textual data were grouped and organized according to the interview questions. In

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145 U.S. Green Building Council, "USGBC: U.S. Green Building Council," Home page, 2009, http://www.usgbc.org/.

146 "NC-v4.1 EQc7: Daylight | LEEDuser," accessed December 24, 2019, https://leeduser.buildinggreen.com/credit/NC-v4.1/EQc7.

this way, every participants' responses to the specific questions became available to manage the broad set of data.

The unstructured, raw data was needed to be converted into meaningful insights to be able to answer this thesis' research questions. For this reason, the qualitative data was examined by adopting thematic content analysis. The analysis type can be applied for any kind of communication materials such as printed or visual media, oral interview conversations, and written researcher observations.[147] Thematic content analysis is stated as "a research technique for the objective, systematic, and quantitative description of the manifest content of the communication."[148] The analysis method is defined as classifying written or spoken materials into designated categories that have similar implications.[149] These categories inhere both literal and concealed meanings of data.[150]

The thematic content analysis consists of inductive and deductive approaches for the determination of categories and themes.[151] In this study, the inductive content analysis approach was selected and applied. The inductive method was initiated by selecting transcriptions as the primary unit of analysis. The transcriptions were examined and coded by reading each sentence word by word. As an interpretive coding method, process coding was used for investigating the participant's feedback. The process coding generally uses verbal-nouns (gerunds) to express the action in the data.[152] This method is recommended by Saldana[153], for detecting simple

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[147] William Albig, "Content Analysis in Communication Research. Pp. 220. Glencoe, Ill.: The Free Press, 1952.," *The ANNALS of the American Academy of Political and Social Science* 283, no. 1 (September 8, 1952): 197–98, https://doi.org/10.1177/000271625228300135.
[148] Ibid.
[149] Francesca Moretti et al., "A Standardized Approach to Qualitative Content Analysis of Focus Group Discussions from Different Countries," *Patient Education and Counseling* 82, no. 3 (March 2011): 420–28, https://doi.org/10.1016/j.pec.2011.01.005.
[150] Hsiu Fang Hsieh and Sarah E. Shannon, "Three Approaches to Qualitative Content Analysis," *Qualitative Health Research* 15, no. 9 (2005): 1277–88, https://doi.org/10.1177/1049732305276687.
[151] Ji Young Cho and Eun Hee Lee, "Reducing Confusion about Grounded Theory and Qualitative Content Analysis: Similarities and Differences," *Qualitative Report* 19, no. 32 (2014): 1–20.
[152] Johnny Saldaña, "The Coding Manual for Qualitative Researchers (No. 14)," *Sage*, 2016.
[153] Ibid.

noticeable activities and thoughts inhered in the data. Process coding is suitable for those who investigate "ongoing action/interaction/emotion taken in response to situations, or problems, often with the purpose of reaching a goal or handling a problem”.[154] The coding process was conducted by a widely used mixed-method and qualitative data analysis software program named Nvivo 12.[155] During coding, it was tried to be open-minded and creative to avoid personal bias.

Initially, the emerging codes grouped under similar clusters and those clusters transformed into categories. While assigning codes to categories, it was realized that some codes serve more than one category. Instead of axial-coding, all process codes were distributed according to their relevancy to the categories. The reason for selecting this method was a conscious decision to avoid the reduction of the codes. Consequently, some of the codes were linked to just a single category, while the others were linked to two or even more categories. Next, the underlying patterns and commonalities between categories were identified. According to the hierarchy, importance, and relevancy between the categories, conceptual themes emerged. Similar to the followed coding strategy, some of the categories were linked to more than single themes. The codes, categories, and themes and how they are connected constitute the main results of the study. The findings of the qualitative analysis were presented in the following sections.

Apart from the qualitative thematic analysis, the transcriptions were translated to English for Nvivo 12’s word cloud analyses. The word cloud of analysis examines how often each word appears in the transcriptions and gives the most commonly used similar words as an outcome of the analysis. In addition, it visualizes hierarchically the often pronounced words as a diagram. This type of analysis contributed to the

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[154] Juliet Corbin and Anselm Strauss, *Basics of Qualitative Research (3rd Ed.): Techniques and Procedures for Developing Grounded Theory*, *Basics of Qualitative Research (3rd Ed.): Techniques and Procedures for Developing Grounded Theory*, 2012, https://doi.org/10.4135/9781452230153.

[155] “Buy NVivo Now | NVivo,” accessed December 25, 2019, https://www.qsrinternational.com/nvivo/nvivo-products/nvivo-12-plus.

research by providing valuable insights when identifying general concept themes. It supports the research as an essential numerical tool for in-depth qualitative analysis.[156]

### 5.9.4 Qualitative Data Analysis: SWOT

SWOT is a qualitative data analysis method that can be applied to various fields, and it is an acronym that symbolizes for Strengths, Weaknesses, Opportunities, and Threats. Swot is a useful qualitative method to comprehend the internal and external potentials of an entity, which can be a product, company, or project (*Figure 5.11*).[157]

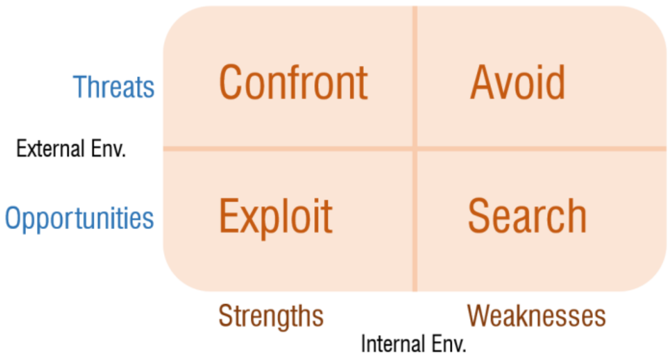


*Figure 5.11.* SWOT's environmental trends

The method helps researchers to understand the entity's internal capabilities along with its environmental trends in a summative way. SWOT is generally employed in the industry to assess the current condition of a company and to identify its future development plan, but its adoption by academia is also accepted.[158] The

[156] Carmel McNaught and Paul Lam, "Using Wordle as a Supplementary Research Tool," *Qualitative Report* 15, no. 3 (2010): 630–43.
[157] Albert Rizzo and Gerard Jeunghyun Kim, "A SWOT Analysis of the Field of Virtual Reality Rehabilitation and Therapy," *Presence: Teleoperators and Virtual Environments*, 2005, https://doi.org/10.1162/1054746053967094.
[158] Maria Mercieca et al., "Swot Analysis," *Pharmaceutical Technology*, 2016, https://doi.org/10.4337/9781784712082.00015.

classification for SWOT analysis can be performed by categorically identifying the collected data according to the following criteria;

- A strength can be defined as the internal capability to reach individual goals and objectives of an entity.[159]
- A weakness is an internal limitation, flaw, or a fault of the entity that hinders the momentum in the direction of its predefined goals.[160]
- An opportunity is basically a factor in the external environment that may accelerate the growth of an entity, and it envisages the future potentials of an entity by examining current trends of an environment.[161]
- A threat is a disadvantageous external circumstance that limits the dynamic growth of an entity. It causes environmental barriers that may affect the entity to reach its goals successively.

In order to present the results more intensively and concisely for the research, the SWOT method was found suitable for the study. During the interviews, specific questions were asked in accordance with the SWOT methodology. Finally, HoloArch's prominent SWOT features were identified and presented in the following section.

## 5.10 Results and Discussion

### 5.10.1 Quantitative Findings and Discussion: Questionnaires

The evaluation of the HoloArch 2.0 was performed with twenty-one participants, and five of them were asked again to attend the user study. The comparative results

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[159] Ibid, 157.
[160] Ibid, 158.
[161] Marilyn M. Helms and Judy Nixon, "Exploring SWOT Analysis – Where Are We Now?: A Review of Academic Research from the Last Decade," *Journal of Strategy and Management*, 2010, https://doi.org/10.1108/17554251011064837.

presented in this chapter are based on the responses given by the 5 participants for HoloArch 2.0 with HTC Vive (collected at METU workshop) and HoloArch 3.0 with HTC Vive (collected at the user study). Apart from the workshops, a more comprehensive method was followed in the examination and interpretation of the questionnaires since HoloArch 3.0 was a completed tool. In this study, the subscales and statistical analyses were conducted to validate the final findings.

#### 5.10.1.1 System Usability Scale (SUS)

Table 5.3. *SUS scoring table*[162]

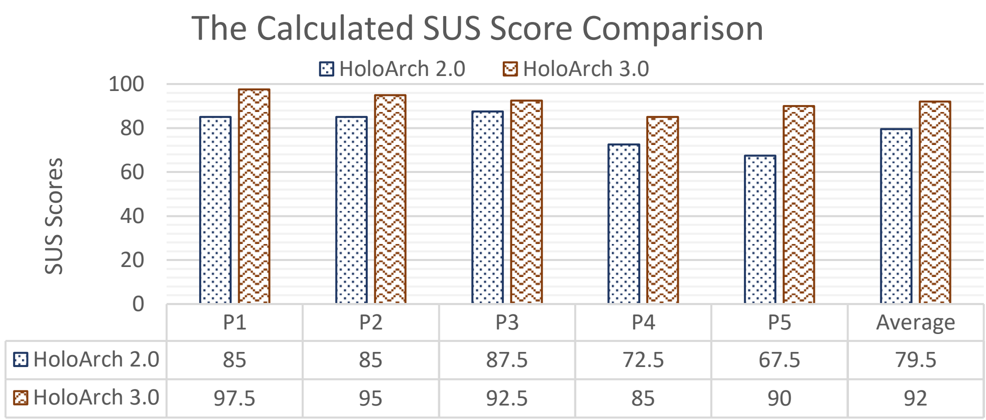
| Grade | SUS | Percentile range | Adjective | Acceptable |
|---|---|---|---|---|
| A+ | 84.1-100 | 96-100 | Best Imaginable | Acceptable |
| A | 80.8-84.0 | 90-95 | Excellent | Acceptable |
| A- | 78.9-80.7 | 85-89 | | Acceptable |
| B+ | 77.2-78.8 | 80-84 | Good | Acceptable |
| B | 74.1 – 77.1 | 70 – 79 | | Acceptable |
| B- | 72.6 – 74.0 | 65 – 69 | | Acceptable |
| C+ | 71.1 – 72.5 | 60 – 64 | OK | Acceptable |
| C | 65.0 – 71.0 | 41 – 59 | | Marginal |
| C- | 62.7 – 64.9 | 35 – 40 | | Marginal |
| D | 51.7 – 62.6 | 15 – 34 | Poor | Marginal |
| F | 25.1 – 51.6 | 2– 14 | | Not Acceptable |
| F | 0-25 | 0-1.9 | Worst Imaginable | Not Acceptable |

SUS questionnaires were gathered from the participants and then were analyzed via IBM SPSS. Since there are no subscales in this particular questionnaire, a more holistic approach was followed in the interpretation of the findings. SUS is widely used in the literature, and a structured scoring sheet is also available for the researchers who may want to compare and evaluate the success of their outputs

[162] Ibid, 162.

(*Table 5.3*). The participants' answers were calculated according to the SUS scoring calculations.[163] It is crucial to state that the negative questions in the questionnaires were reversed in order to compose a coherent score as recommended in the Broke's paper.[164]

The user study's findings, along with the previous workshop findings, were illustrated comparatively in *Figure 5.12*. The table shows each participant's individual scores and the total average scores both for HoloArch 2.0 and 3.0. The total average of the questionnaires revealed as 79.5 with an ST.D. of 8.9 for HoloArch 2.0 and 92.0 with an ST.D. of 4.8 for HoloArch 3.0.




| | P1 | P2 | P3 | P4 | P5 | Average |
|---|---|---|---|---|---|---|
| HoloArch 2.0 | 85 | 85 | 87.5 | 72.5 | 67.5 | 79.5 |
| HoloArch 3.0 | 97.5 | 95 | 92.5 | 85 | 90 | 92 |

*Figure 5.12.* SUS score comparison

According to the scoring sheet in *Table 5.3*, HoloArch 3.0 was turned out to be defined as "excellent" and be graded as "A" in the system usability assessment. In addition to that, the same participants were graded HoloArch 2.0 as "B" and defined as "good" as well.

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[163] James R Lewis and Jeff Sauro, "Item Benchmarks for the System Usability Scale," *Journal of Usability Studies* 13, no. 3 (2018): 158–67, http://uxpajournal.org/wp-content/uploads/sites/8/pdf/JUS_Lewis_May2018.pdf.
[164] Ibid, 113.

It is possible to state that all of the participants were found HoloArch 3.0 more successful than the previous version in terms of system usability by looking at the table. However, in order to be sure about whether these differences are reliable or not, statistical analysis between the results must be conducted. For this reason, various analysis methods were followed, including descriptive analyses and reliability tests.

The statistical analysis results are shown in *Table 5.4.* At first view to the table, more consistency can be observed in the participants' scores for HoloArch 3.0 by comparing the standard deviations. This result supports the idea that participants arrive at a consensus that HoloArch 3.0 was more usable than the previous version. On the other hand, the reliability of the participant responses was found "high", since the calculated Cronbach's alpha (α) value was higher than 0.5 (0.756 > 0.5). In summary, these results show that HoloArch 3.0 is excellent in terms of usability with the newly added features, and it is more usable than HoloArch 2.0.

Table 5.4. *SUS's statistical analysis results*

| HoloArch 2.0 Mean SUS Score | HoloArch 3.0 Mean SUS Score | Reliability Test Cronbach's Alpha (α) |
|---|---|---|
| 79.5 (ST.D. ± 8.9) | 92 (ST.D. ± 4.8) | 0.756 |

#### 5.10.1.2 Presence Questionnaire (PQ)

Similar to SUS, PQ was analyzed by following the same method. Differently, PQ questionnaires have subsections that represent diverse characteristics of the tool. A total of 19 questions was asked in order to evaluate HoloArch's affordance in presence by focusing on the questionnaire's subsections, including "realism", "possibility to act", "quality of interface", "possibility to examine", and "self-evaluation of performance". Apart from SUS, a system's overall performance is separately calculated for each subsection and then aggregated for a total presence score. For understanding the success of HoloArch's presence capabilities, a scoring sheet was found appropriate to be adopted. The scoring sheet can be seen in *Table 5.5,* which shows the minimum scores for a successful outcome.

Table 5.5. *Scoring for PQ*[165]

*Revised by the UQO Cyberpsychology Lab[166] (Translated from French)*

| | Average | ST.D. |
|---|---|---|
| Total | 104.39 | 18.99 |
| Realism | 29.45 | 12.04 |
| Possibility to act | 20.76 | 6.01 |
| Quality of interface | 15.37 | 5.15 |
| Possibility to examine | 15.38 | 4.90 |
| Self-evaluation of performance | 11.00 | 2.87 |

The presence questionnaire results were shown in *Figure 5.13.* For evaluating these results, the scoring sheet was used to understand the application's success. Accordingly, HoloArch 3.0 passed in all of the subsection threshold levels with marginal differences. The total score of 120.4 was noted for HoloArch 3.0 and this was almost %15 above the threshold level. This finding might confirm that HoloArch is a successful tool that provokes the sense of being in the IE. However, HoloArch 2.0 failed to collect enough scores in order to exceed the threshold level in the overall presence capability. In detail examination, it could be seen that the quality of interface and self-evaluation of performance subsections were below the threshold level. This finding might show the new developments in HoloArch 3.0 had a visible impact on the participants' thoughts. A similar result with the SUS questionnaire's findings for the version differences can be seen in the figure. Therefore it might be said that HoloArch 3.0 was far more successful than the previous to provide a sense of presence.

[165] Ibid, 114.
[166] "Laboratoire de Cyberpsychologie de l'UQO – La Cyberpsychologie Pour Le Bien-Être de La Santé Mentale," accessed January 13, 2020, http://w3.uqo.ca/cyberpsy/.

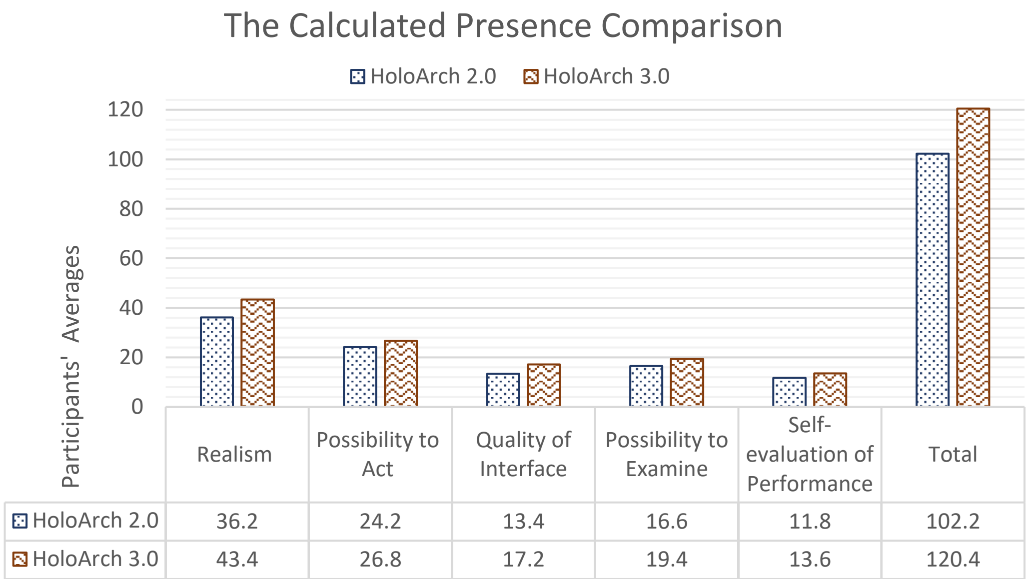


*Figure 5.13.* Presence comparison

For the validation of the differences and the reliability of the results, statistical analyses were conducted in the same way as SUS. The results can be seen in *Table 5.6.* When the ST.D.'s were examined, more consistent responses were given to HoloArch 3.0 by the participants, except for the possibility to examine subsection. This may be explained by the fact that some actions do not have the same effect on everyone. As can be seen in the following sections, several dissensuses were observed among the participants. The collected data in total were found as "reliable" in the reliability analysis (0.855, $\alpha > 0.5$). However, when the subsections were examined, "quality of interface" was not found reliable enough (-0.109, $\alpha < 0.5$). The reason for that might be related to that the drastic change in the scores on "the quality of UI" section may cast doubts on the reliability of the results. However, it is highly likely that this change depends on the increase in the values of quality of UI in the newer version considering that HoloArch 3.0 had higher mean values in terms of interface. To conclude, these findings imply that HoloArch 3.0 is successful in providing a sense of presence and is more advanced to provide that in comparison with the previous version.

Table 5.6. *PQ's statistical analysis results*

| | HoloArch 2.0 Mean PQ Score | HoloArch 3.0 Mean PQ Score | Reliability Test Cronbach's Alpha (α) |
|---|---|---|---|
| Total | 102.2 (ST.D. ± 12.19) | 120.4 (ST.D. ± 6.46) | 0.855 |
| Realism | 36.2 (ST.D. ± 6.57) | 43.4 (ST.D. ± 3.64) | 0.845 |
| P. Act | 24.2 (ST.D. ± 2.58) | 26.8 (ST.D. ± 1.64) | 0.926 |
| Q. Int | 13.4 (ST.D. ± 3.28) | 17.2 (ST.D. ± 1.64) | -0.109* |
| P. Ex. | 16.6 (ST.D. ± 1.51) | 19.4 (ST.D. ± 1.81) | 0.507 |
| Self Ev. | 11.8 (ST.D. ± 1.48) | 13.6 (ST.D. ± 0.54) | 0.684 |

*Since $\alpha$ value is less than 0.5, the results were not found reliable.

#### 5.10.1.3 Technology Acceptance Model (TAM)

Different from the other questionnaires used in the study, the adopted TAM questionnaire does not have a structured question set nor a scoring sheet to compare the results. Therefore the results were examined only numerically. For the user study, the most related three subsections of the TAM model were selected for the study, including perceived ease of use, behavioral intention, and perceived enjoyment. After the data collection, the questionnaire was analyzed using descriptive statistics. The results were given in *Figure 5.14* comparatively for each subsection, along with each version. Similar to previous questionnaires, the preliminary results show that HoloArch 3.0 was had successful passing scores in the TAM's perceived ease of use (MV 9.4/10.0), behavioral intention (MV 9.7/10.0), and perceived enjoyment (MV 8.6/10.0) subsections. These results might show that using HoloArch 3.0 would be free of effort, be preferred intentionally by the participants in the future, and be fun for the participants. Even though HoloArch 2.0 had fewer scores than HoloArch 3.0, it was also found successful in satisfying the subsections to some degree. By comparing the results, it could be seen that most of the improvements on HoloArch 2.0 were taken place in the perceived enjoyment subsection with an increment of 1.4. These results could be related to the impact of the new UI design and newly added features.

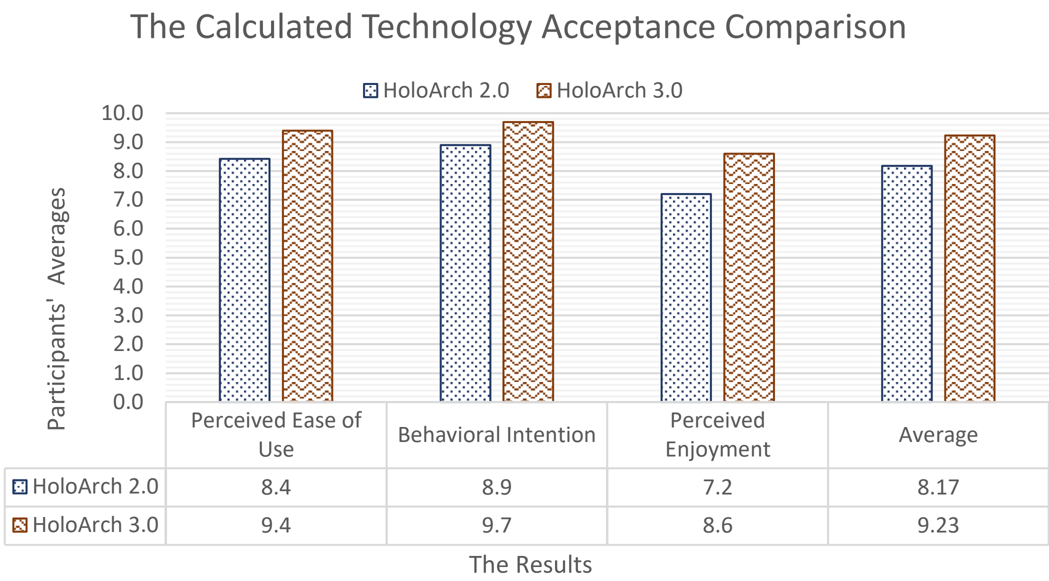


*Figure 5.14.* TAM comparison

On the other hand, the collected data in total were found "robust" in terms of reliability since the calculated Cronbach's alpha (α) value was higher than 0.5 (0.825 > 0.5). The statistical results can be seen in *Table 5.7.*

Table 5.7. *TAM's statistical analysis results*

| | HoloArch 2.0 Mean SUS Score | HoloArch 3.0 Mean SUS Score | Reliability Cronbach's Alpha (α) |
|---|---|---|---|
| Total | 8.3 (ST.D. ± 1.37) | 9.3 (ST.D. ± 0.62) | 0.825 |
| Per. E. | 8.4 (ST.D. ± 1.28) | 9.4 (ST.D. ± 0.48) | 0.757 |
| Beh. In. | 8.9 (ST.D. ± 1.47) | 9.7 (ST.D. ± 0.44) | 0.707 |
| Per. En. | 7.2 (ST.D. ± 1.98) | 8.6 (ST.D. ± 1.51) | 0.943 |

*Since $\alpha$ value is less than 0.5, the data was not normally distributed.

HoloArch 3.0's mean values for every section were found higher than the previous version, and the data set was reliable. In conclusion, HoloArch 3.0 was found sufficient enough to provide easy usability, enjoyment, and to be preferred intentionally by the participants and these capabilities of HoloArch 3.0 were better compared to the previous version.

### 5.10.2 Quantitative Findings and Discussion: Daylighting Results

All of the participants showed a high interest in HoloArch and stayed more than 45 minutes in the environment without any complaints and focused on their performative designs. The architectural design outcomes, along with their planned spaces for each participant, are illustrated in *Figure 5.15.*

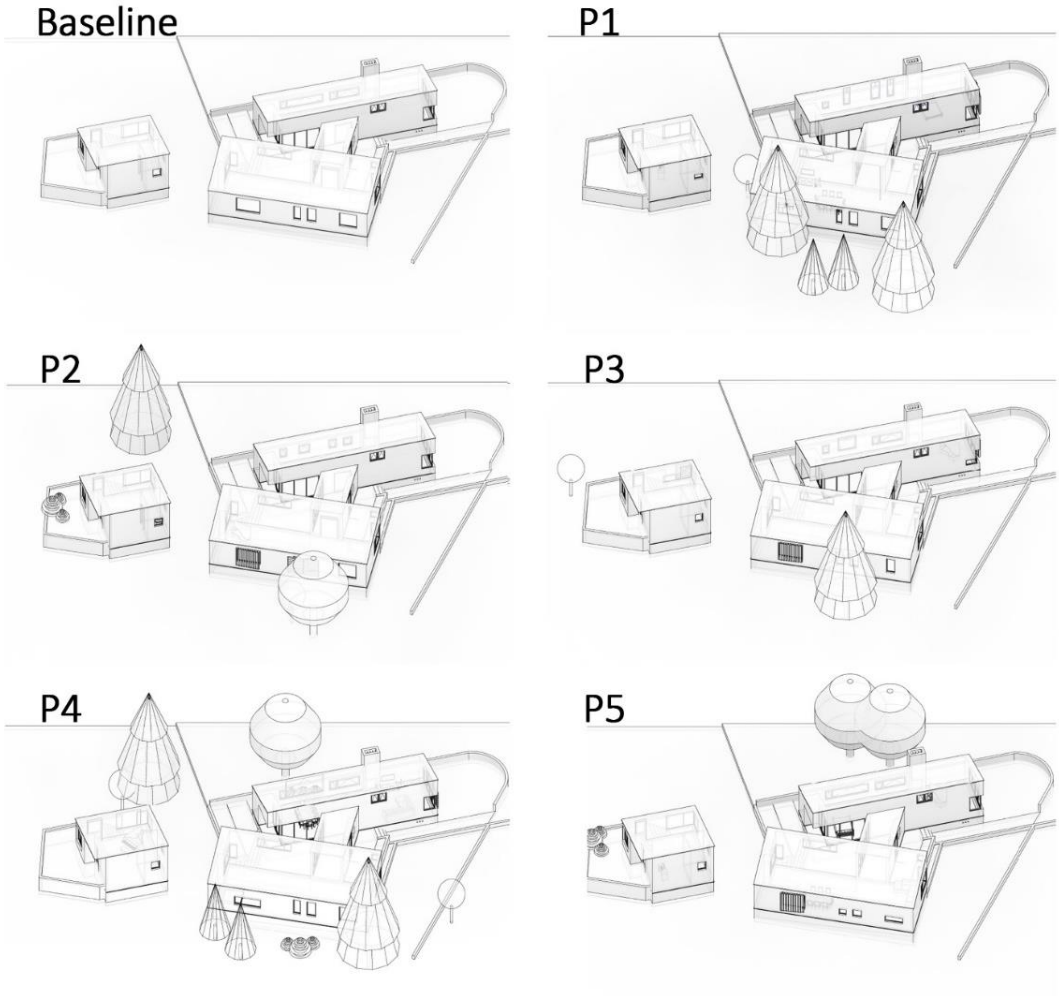


*Figure 5.15.* The design outputs of the participants

Hence design is subjective; all of the participants handled the daylighting design problems of the baseline model in their own distinct way. As a consequence, five different designs with diversified daylighting performances emerged. While some of the participants tried to control excessive daylighting by planting a lot of trees to the environment ( e.g., P1 and P4); some of them tried to handle the problem by focusing on changing the dimensions of the opening elements (e.g., P2 and P5); and also many others attempted to place shading devices and change the materials of the opening elements. Each participant interpreted the analysis results in their own volition and arranged the internal organization of the spaces accordingly. For example, while P2 put the piano on the north-western façade by saying that:

> "It would be nice to play the piano as the sun goes down, so I will put the piano close to the western windows." (P2)

P4 followed another strategy by placing the piano in east façade and added that:

> “ I would prefer to play piano in an isolated place during the day, but I don't want to face glare problems at sunrise...it is better to place some trees in front of the window as well.” (P4)

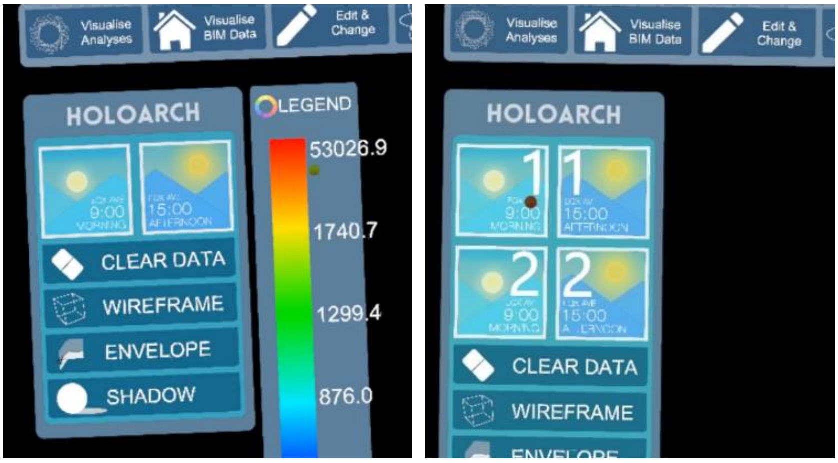


*Figure 5.16.* Daylighting analysis visualization tab and comparative visualization tab for final and baseline simulations (where yellow represents high lux values)

After the design actions completed, daylighting simulations conducted with the edited geometry in Revit, and results were shown to the participants, along with the initial simulations (*Figure 5.16*). The comparison feature allowed the participants to understand how their design actions reshaped the analysis results by switching back and forth between the baseline and the final result’s simulations.

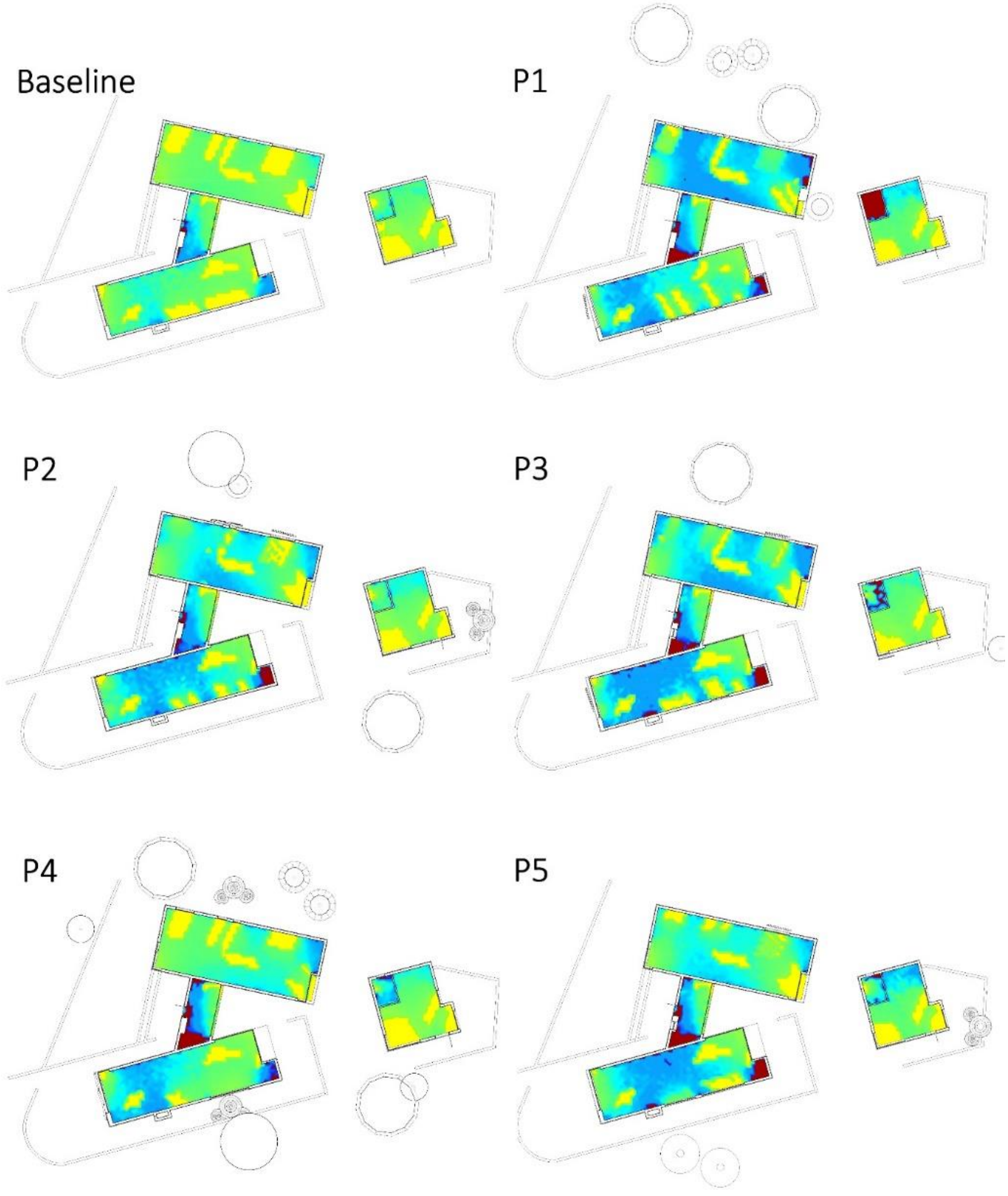


*Figure 5.17.* Daylighting analysis results of the design outputs (where yellow represents high lux values)

After the experience was over, the analysis results of the users were visualized again in Revit, and the numerical data of the analyzes were obtained. The participant simulation results visualized in Revit can be seen in *Figure 5.17*. Based on these results, it could be inferred that all the participants made positive decisions regarding their daylighting design. The yellow areas where sunlight was concentrated intensively in the baseline have been dramatically reduced in all of the design outputs. If one can look at the figure carefully, there is little difference taken place in the daylighting analysis of the detached building block. This might be due to the fact that the participants mostly preferred to concentrate on the big building block or thought that daylighting performance was sufficient in that particular block. In addition to the visual results, the numerical benchmark comparison provided by Revit Insight was performed for all of the design outputs.

Table 5.8. *Daylighting Analysis Results of the Participants (Pass: Pass scores dictated by LEED v4 EQ credit 7 option 2 criteria, BTh: Below the threshold, ATh: Above the threshold)*

| | **9.00 AM Equinox Scores** | | | **3.00 PM Equinox Scores** | | | **Total Equinox Scores** | | |
|---|---|---|---|---|---|---|---|---|---|
| **Models** | **Pass** | **BTh** | **ATh** | **Pass** | **BTh** | **ATh** | **Pass** | **BTh** | **ATh** |
| **Baseline** | 89% | 0% | 11% | 87% | 0% | 13% | 76% | 0% | 23% |
| **P1** | 88% | 4% | 8% | 92% | 2% | 5% | 82% | 5% | 13% |
| **P2** | 91% | 1% | 8% | 92% | 1% | 7% | 84% | 2% | 15% |
| **P3** | 88% | 4% | 8% | 92% | 2% | 6% | 82% | 4% | 14% |
| **P4** | 91% | 2% | 7% | 88% | 2% | 11% | 80% | 3% | 17% |
| **P5** | 89% | 4% | 7% | 91% | 2% | 7% | 82% | 4% | 14% |
| **Average(P1-5)** | 89% | 3% | 8% | 91% | 2% | 7% | 82% | 4% | 15% |

According to the results indicated in *Table 5.8*, all users were able to improve the daylight performance of the building positively and converged to the Leed criteria which were challenging to reach. According to the table, P2 and P4 improved the daylight control positively, while all participants improved the critical western sun with a visible difference. However, most of the participants were focused on highly illuminated areas and were ignored insufficiently illuminated areas. This approach resulted in over-obstruction of daylight penetration to some areas of the building during morning and afternoon. When looking at the individual results and overall averages of all participants, daylight performance was noticeably improved. As a result, it can be said that daylight and architectural design can be done in virtual environments by using HoloArch and this application contributes positively to building performance.

### 5.10.3 Qualitative Findings and Discussion: Word Cloud

The word cloud analysis for Nvivo 12 queries the most mentioned words in the transcriptions and can create a representative word cloud by hierarchically composing the stated words. This type of analysis cannot directly present findings or cannot allow making certain deductions. However, it can be useful to frame general themes or concepts before initiating the thematic content analysis. As an outcome of the user study, a diagram was prepared that can be seen in *Figure 5.18* by eliminating some word types such as articles (e.g., the, a, an), conjunctions (e.g., and, however, but), and prepositions (e.g., on, at, in).


*Figure 5.18.* The Word cloud

According to the diagram, the most mentioned ten words appeared as; “think”, “design”, “building”, “directly”, “change”, “environment”, “model”, “daylighting”, “different”, and “virtual reality”. The most negative words emerged as; “difficult”, “usability”, “problems”, and “limited”. On the other hand, the most used positive adjectives were revealed as; “different”, “useful”, “effective”, “comfortable”, “interactive”, “enjoyable”, “important”, and “easier”. By looking only at the word cloud intuitively, it might be concluded that mostly positive opinions about the application were presented in general since negative words are not commonly used. The participants preferred to talk about the changes in design and daylighting of the building/model/environment in particular. Apart from that, “think” was emerged as the most pronounced word. This can be interpreted that the given interview was mostly based on the participants’ own thoughts and reflect what the participants really thought about the project. The negative words could be explicated as the participants might have difficulties to control the environment, and they might spot the limited aspects of HoloArch. Even though these inferences were based on biased interpretations made by the author, the outcomes of the study appeared in the upcoming section as parallel to the word cloud analysis commentary.

#### 5.10.4 Qualitative Findings and Discussion: SWOT

The SWOT method was used to find out the participants’ subjective preferences on the most striking features of the tool, rather than revealing its affordances emphasized in the interviews. For this reason, SWOT analysis results are different from the thematic content analysis. The questions regarding the understanding of participants’ personal preferences were asked as parallel to the swot method. Subsequently, the revealed results from each participant were ranked according to the frequency of mention method. The three most mentioned comments were selected and discussed for each swot category (*Table 5.9*).

Table 5.9. *The SWOT Analysis Matrix of HoloArch*

| **The SWOT Analysis Matrix of HoloArch** | |
|---|---|
| *Strengths* | *Opportunities* |
| +++ Integration of Different Concepts<br>++ Instantaneous Scaling<br>+ Bidirectional Workflow | +++ Acceptable as a free plug-in<br>++ Educative Tool<br>+ Applicable for other performative simulations |
| *Weaknesses* | *Threats* |
| --- Non-simultaneous Simulation<br>-- Usability Problems<br>- Control and Navigation | --- Technological Limitations<br>-- Biological Limitations<br>- Not suitable as a professional tool for now |
| INTERNAL FACTORS | EXTERNAL FACTORS |

### 5.10.4.1 The Strengths

The strengths of the tool were based on what participants liked the most about HoloArch. The most potent characteristics of HoloArch were revealed as;

**Integration of Different Concepts:** Four of the participants agreed that one of the substantial parts of HoloArch was its multipurpose nature. They emphasized the integrity it provides by giving examples from HoloArch's features. Some of them stated that HoloArch could facilitate multiple functions intrinsically by allowing design actions, interactions with BIM models, interpretation of daylighting results, space planning, wandering around, being inside the model, seeing a building in different scales, and such. Some participants mentioned that HoloArch brought together a lot of different concepts and offered a unique practice they had never experienced before. A participant stated that:

> "HoloArch brings a lot of stuff together, and it makes everything much easier." (P2)

**Instantaneous Scaling:** Three of the participants stated that they found it useful and perceptive to switch between different scales simultaneously. This feature allowed them to understand the building, along with its spatial characteristics in an augmented way. They pointed out that HoloArch provided familiar experiences by representing the building similar to craft models with smaller scales and, at the same time, extraordinary experiences by visualizing the building in its true scale before even built.

**Bidirectional Workflow:** Two of the five participants agreed on the cyclic flow between platforms was the most prominent feature of the tool, and this feature made HoloArch differentiate from other virtual reality applications. A participant states his excitement by saying that:

> "I think the bidirectional flow presented was extremely significant, and it is the best part of this application...a user can see what he/she designs and can go back to Revit and continue to work". (P2)

#### 5.10.4.2 The Weaknesses

The weaknesses of the tool consisted of noticeable limitations, missing features , and the struggles faced during the experience by the participants.The most negative aspects of HoloArch were found as;

**Non-simultaneous Simulation:** Similar to the outcomes achieved in previous workshops, this missing feature was the weakest aspect of HoloArch again. Since the simulations are taken by Revit, and they take for a long time, the participants cannot simultaneously see how their design actions affect the daylighting performance of the building. The weakest aspect of the application was expressed by all of the participants. The integration of this feature has not been successfully accomplished because a custom made daylighting calculations exceed the know-how of the developers. Two participants argued that adding this feature in HoloArch's framework would make the application a more effective design tool to accelerate design processes and to reach final designs more efficiently.

**Usability Problems:** Although the usability issues placed into focus after the workshops, the participants stated some usability problems for HoloArch 3.0 again. Almost all of the participants were disturbed at least one working principle of

HoloArch. However, it was not stated as crucial as non-simultaneous daylighting visualization. Two of the participants were mentioned that the UI was too big, as it sometimes precluded to reach the model. Even though an action for changing the location of UI was presented, they did not want to be bothered consistently by relocating it. Two other participants expressed that they could not predict how their actions have come out, so they sometimes had difficulties using and adapting to HoloArch. However, they were found HoloArch easy to use except for some minor flaws in general.

**Control and Navigation:** Three of the participants did not find the design of the rotation command intuitive enough because it took a bit long time adapting themselves to its working principle completely. They found the increment buttons appointed for rotation degrees as impractical, and they wished they could directly control degrees via physical buttons on HTC Vive’s controller. Although only three buttons were assigned to Vive's controller, participants often confused about how the buttons worked. Two other participants indicated that experiencing the building in its true scale was hard for wayfinding in the environment because they thought a user might be lost very quickly. For solving that problem, both of the participants suggested an additional mini-map feature, which could show users where they are in the environment.

#### 5.10.4.3 The Opportunities

The most prominent future potentials of HoloArch emerged as;

**Acceptable as a free plug-in**: All of the participants agreed that they might use this app as a free plug-in if it would be launched in the Autodesk store. Since immersive appliances usage at home is not common in Turkey[167], they could not be definitely

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[167] Tugay Arat and Sedef Baltacioğlu, “Sanal Gerçeklik ve Turizm Virtual Reality and Tourism,” *Selçuk Üniversitesi Sosyal Bilimler Meslek Yüksekokulu Dergisi* 19, no. 1 (2016): 103–18.

sure whether they would use it at home or not. Two of the participants said that if they had access to an immersive system at home, they would undoubtedly implement their studio projects to HoloArch to understand and change their project's daylighting design. Surprisingly, a participant added that she would not be bothered to pay for HoloArch if the main usability problems were fixed.

**Educative Tool**: Four of the participants pointed out to HoloArch's educative potential by emphasizing that it allows understanding the performance and architecture at the same time. A participant supported his comment by saying that:

> "HoloArch constructs a bridge between engineering's straight forward solutions and architecture's ill-defined problems to help designers to design functional buildings. It not only visualizes but it guides as well." (P1)

Two participants with less knowledge of performative simulations stated that their experience taught them new things and that they were not aware that daylight simulations were so interrelated with architecture. They said they learned there were many possibilities to manipulate the results by intervening in architecture. A participant said:

> "It (HoloArch) allows us to understand the importance and effectiveness of daylighting and to find new connections in design." (P4)

**Applicable for other performative simulations:** Four of the participants expressed that the immersive environments were an excellent solution to comprehend and understand complex performative simulations and should not be applied only for daylighting but also wind, energy, and similar. The participants stated that HoloArch served as an interactive "serious game" for designers to understand the importance and performance of daylighting in buildings, and the system should also be applied for other types of performative dynamics of the building assessment.

#### 5.10.4.4 The Threats

The possible barriers that HoloArch may face in the future were stated by the participants as;

**Technological Limitations:** Four of the participants remarked that technology was not advanced enough for people to leave computers completely aside and to start working only in immersive environments. A participant expressed his feeling by saying that:

> "The resolution of the VR system is poor-quality cannot compete with computers, and the state of art computers' performance is not enough to provide photorealistic imagery without any lags. ...the same thing is also valid for MR tools as well, HoloLens' field of view was really narrow; it totally distracts you to perform something."(P3)

The participants stated that if we would want to keep using immersive systems in the future, these technologies should be enhanced, and this implication is also valid for HoloArch as well. Similarly, the technological problems were also stated in the simulation visualization part of the experience. Since there are a lot of colorful spheres distributed in the building floor, the used computer's power was not enough to prevent lags, and it created motion-sickness for some of the participants.

**Biological Limitations**: Three of the participants pointed out the biological limitations might limit the growth rate of the immersive industry in the future. Since Vive and similar VR gadgets use pixels very close to eyes to provide an immersive experience, almost all of the participants rubbed their eyes immediately after they have taken out of the HMD. They agreed on discomfort problems, including motion sickness, nausea and eyesores existed and must be fixed for extended use. A participant pointed out this problem by saying that:

> " ...a person can work by looking at a computer screen for 8 hours without any discomfort, but I think it is very challenging to withstand immersive displays more than an hour." (P1)

and another participant said:

> "In order to be able to design and control the environment in immersive platforms, I need to be always on the move. , is very tiring and dizzying." (P4)

**Not Suitable as a Professional Tool for Now**: two of the participants indicated that the HoloArch project was not ready as a business enterprise for now and cannot be used at professional practice because of its limited range of features, some of the concurrent usability problems and the delays during re-simulation stages. Some of the participants stated that HoloArch is not suitable for finetuning or detailing, and revise work was necessary to achieve a final design via Revit but, the HoloArch project was developed for creating an augmented awareness for designers in the early design stages of buildings in terms of daylight. In addition, a participant added that:

> "HoloArch makes it easy to understand everything, and perhaps it is not for senior professionals but certainly suitable for junior designers." (P2)

### 5.10.5 Qualitative Results and Discussion: Thematic Content Analysis

The findings of the qualitative data were presented, along with its explanation and interpretation. After the analysis with the collected data, 83 process codes were detected. These codes were clustered in a total of 19 subcategories. The Sankey diagram of the thematic content analysis results can be seen in *Figure 5.19*. This section was based on data synthesis, reduction because of the vast amount of data.

Since it is not possible to present what all 83 codes stand for, a brief explanation of the parent categories and their overarching themes are included in the thesis. The diagram was decomposed to examine each theme individually. Also, each theme's subcategories and their number of mentions were illustrated in the following breakdown diagrams.

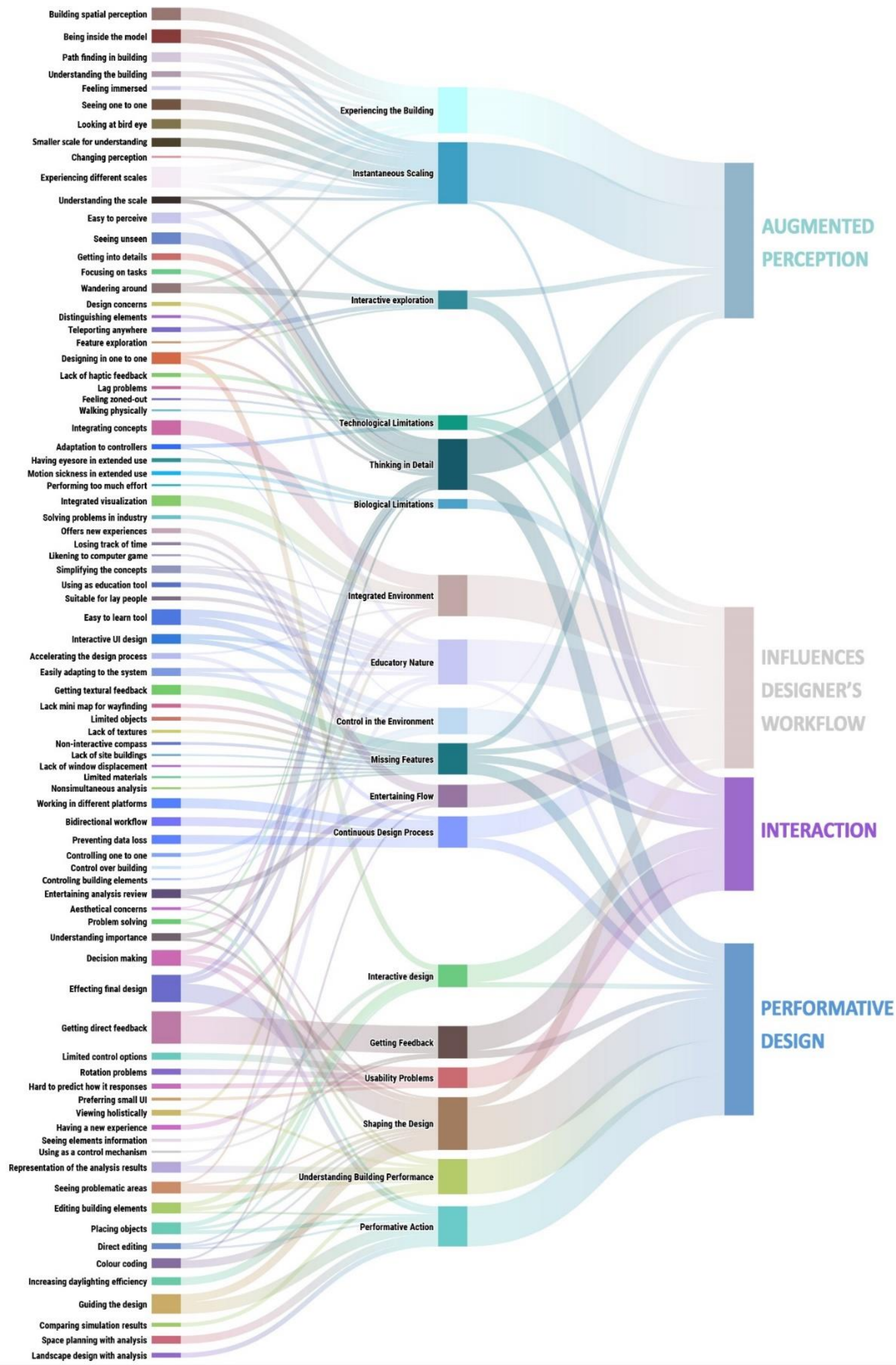


*Figure 5.19.* The Sankey diagram of the emerged themes, categories and codes

#### 5.10.5.1 Influences on Designers' Workflow

A total of 41 codes were merged into 8 categories to constitute an overarching theme. This theme hosts both negative and positive categories and has a total of 174 mentions (*Figure 5.20*).

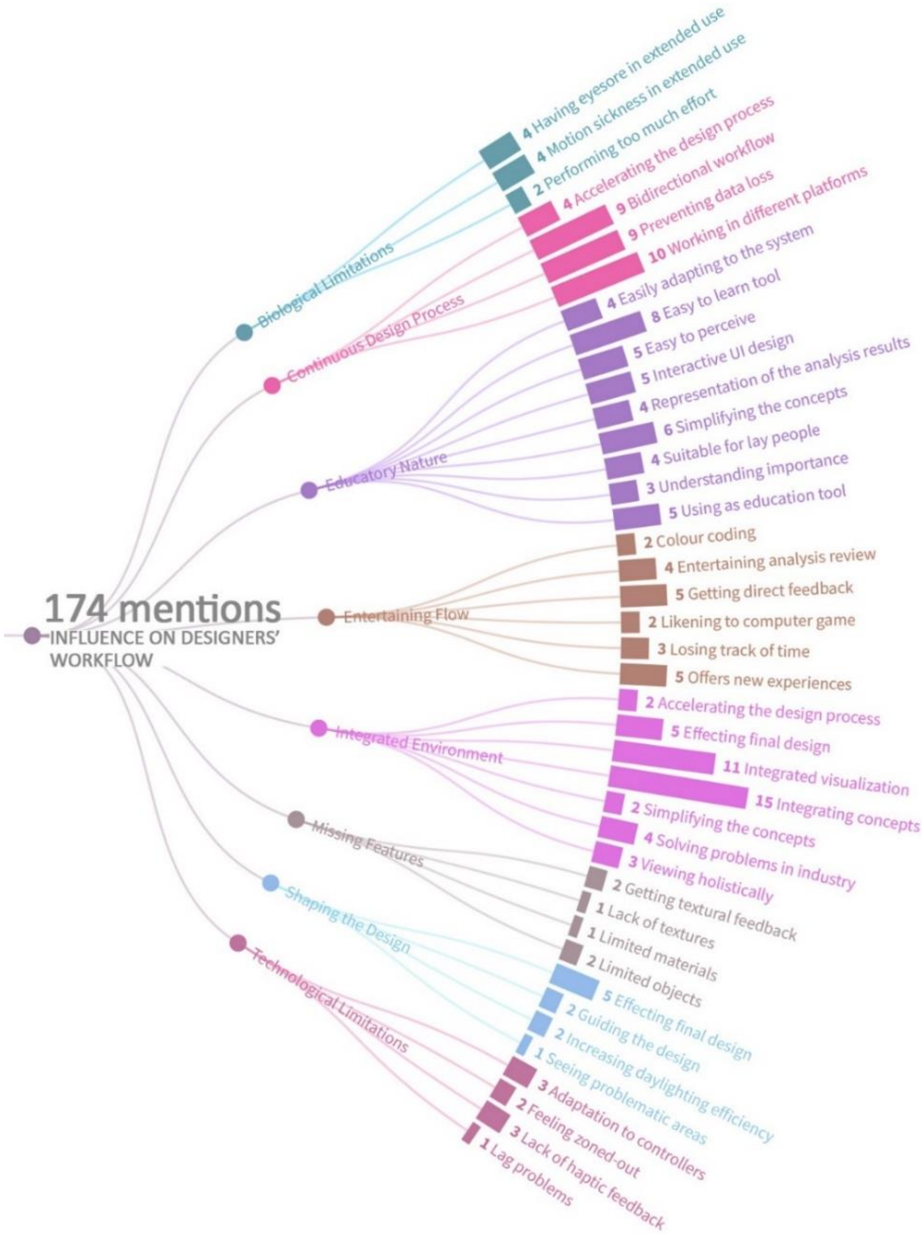


*Figure 5.20.* Breakdown of the Influence on designers' workflow theme

**Adverse inhibitors: Missing Features, Biological, and Technical Limitations**

According to the analysis, designers' workflow can be affected negatively by the technological and biological limitations in present-day conditions, and HoloArch's missing features. The negative aspects caused by future threats may or might affect the workflow. Technological limitations such as adaptation to controllers, feeling zoned out, lag problems, lack of haptic feedback; and biological limitations such as eyesore, motion sickness, performing too much effort might have a bad influence on the designers' workflow. In this topic, a participant stated that:

> "Haptic feedback is a sensory data that is lacking in this experience; you can't feel like it [model] is completely there without the feeling of touch. This is more related to technology, I know. In addition, if we want people to use these tools in the future, adaptation to these systems must be supported to integrate the tools into our design process fully." (P3)

This haptic problem in the participant's statement could be overcome by providing textural feedback by introducing photorealism in the textures. This approach may provide haptic feedback perceptually for the immersive tools similar to HoloArch. Yet, as the participant stated, these limitations are not directly associated with the HoloArch's deficiencies; instead, the limitations are related mainly to the current immature conditions in human evolution and immersive technologies. The findings show that some missing features of HoloArch have an unfavorable impact on the designers' workflow. The most prominent inhibitors emerged as limited objects and materials. Since the tool was a case study and not intentionally developed for professional work, the material and object catalogs were only provided for experiment purposes. The participants think that if a wide variety of materials, objects, and actions would be provided in HoloArch, they could enhance their projects in a more flexible way. Also, the automation delays in daylighting simulations affected their workflows negatively.

**Integrated Environment and Continuous Design Process**

The most effective parent category shaped this theme was the integrated nature of HoloArch. HoloArch brings together many different concepts and makes a positive contribution to the workflow of designers. According to the participant comments, the integration of the concepts accelerates design processes and affects the formation of the final design. Almost all the participants stated that they were struggling with data transfer problems in their professional lives. They mentioned that different platforms generally do not match up with each other during data transfers, and this problem negatively has been affecting their workflows. It was emphasized by the participants that HoloArc had the potential to solve the current industrial problems by bridging between different platforms. In addition, according to the transcriptions, HoloArch simplified different complex concepts and visualized everything in a combined way. Two participants summarized the perks of an integrated design environment by saying these:

> "… we can visualize this data from the early design stages and can integrate it into the process, this can both improve the quality [visual and thermal comfort], energy and daylighting performance of the spaces. In this application, you can see things you don't usually see in plan or section view, so it makes your job easier, and that's a good thing." (P2)

> "At first glance, I thought that [HoloArch] makes a mess by connecting many irrelevant things together, but after using it for 45 minutes, I really understood the things that I call irrelevant were actually pretty essential for daylighting. So, the lesson was learned. I mean, everything is in one environment that makes designing so smooth and easy to manage." (P3)

It can be inferred that the perception of problematic areas, buildings, and performance data allowed participants to make functional and aesthetic design decisions easily. They can shape their performative designs guided by the performative data. They stated that directed guidance provided by performative simulations allowed them to achieve optimum final design solutions and affected their design processes. A participant said:

> "This is an application I can consult from time to time. It enabled us to make changes to the model by seeing the analysis data. It was effective in telling me what to do. Simulations make what you see and add more effective. I was able to establish a problem-solution relationship very visually and comfortably." (P4)

The holistic visualization approach in the IE enabled the detection of problematic areas and the generation of problem-oriented solutions for the participants. Apart from that, bi-directional workflow without any data loss was attracted a great deal of attention by the participants. The Participants expressed that working in a single environment as an architect was impossible to achieve high-quality design, and added that the data loss between different platforms was an inevitable and natural part of their prior design processes. Strikingly, it was revealed during the interviews that some of the participants tend to select which software programs they are going to use before initiating the design process, and they often limit their designs activities according to the allowed actions in the selected software programs. The participants found HoloArch "effective", "handy", and "smooth" in this manner. Talking about this issue, three interviewees said:

> "It is crucial to have data integration between different platforms. We are always dealing with this stuff [data transfers], and wasting our time rather than focusing on our design. It is important to prevent data loss, HoloArch is perfect in that way, but its automation should be accelerated and improved." (P4)

> "I think it is awe-inspiring to be able to use the same model in such an immersive environment. Probably, when I was a student, I mostly complained about not being able to transfer my design to different environments." (P5)

> "I think this is the most powerful feature of the tool, the design process should not be interrupted; this [like in HoloArch] is the way we suppose to design. It[HoloArch] allowed me to reuse data, to continue in my design process…[HoloArch was] definitely fast and effective. If you didn't provide such a feature, I had to note my every single design action and make them again in Revit." (P1)

Overall, these results indicate that HoloArch's integrated nature allows designers to focus on designs uninterruptedly and to shape their designs guided by performative simulations. These features have a significant impact on the designers' workflow and the generation of final designs. The novel approach used in workflow between platforms shows how data preservation, in terms of immersive architectural applications is vital.

### Entertaining Flow and Educatory Nature

The participants often stated that they had a lot of fun in their experiences and did not understand how the time passed. Contrary to the expectations, they did not have any difficulties staying in the virtual environment. From time to time, they said that the application allowed them to design in a way that they have never experienced before. They described their experience as a tedious task but rather a computer game. The participants stated that they preferred the actions more, which gave them direct feedback. For example, two of the participants, while they were placing objects, expressed that using HoloArch was similar to play The Sims, a life simulation game. This can be attributed to the fact that participants remained in the virtual environment without a break until the end of their experience. As frequently encountered in the literature, IE is often found to be entertaining.[168]The HoloArch project also found parallel findings. The innovative approach of the application to design has been evaluated as successful. In this regard, a participant commented:

> "The app was like the Sims, just like my childhood dream. I was in a computer game. It makes you feel like you are playing a game. And it was amusing, I have never felt bored, I could even stay longer if I had time." (P1)

On the other hand, when users were asked about the purpose of this application, the four participants indicated that HoloArch is a training oriented application. Such an impression can be explained by the fact that the simulation visualization used in the application was easy, colorful, perceptible, and was supported by many interactive design actions. Since HoloArch is easy to learn and to adapt, the participants stated that the tool could be a part of their design processes. It is also stated that thanks to the interactive and aesthetic design of the UI, HoloArch had become a tool that could be manipulated by users from all range of ages and professions. A Participant supported this claim by saying:

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[168] Ma, Minhua, Lakhmi C. Jain, and Paul Anderson. "Future Trends of Virtual, Augmented Reality, and Games for Health." Intelligent Systems Reference Library, 2014. https://doi.org/10.1007/978-3-642-54816-1_1.

> "Once again, I realized how vital daylight is for architectural design. I think it serves as a serious game for people who have no knowledge about it [daylighting]. Even someone without knowledge can easily understand instinctually. I think it could be integrated into designers' processes for giving the right choices." (P5)

As a result, thanks to its entertaining, educational, and easy to use nature, HoloArch can make a positive contribution to the workflow of designers.

#### 5.10.5.2 Performative Design

**Adverse inhibitor: Missing Feature**

This theme hosts both negative and positive categories and has a total of 170 mentions (*Figure 5.21*). According to the obtained feedback participants, there were some missing features that affected the performative design in virtual reality negatively. The most prominent missing feature emerged as the lack of visual representations of the textures. Since HoloArch is  an abstract environment without any visual material textures, the participants thought that visual material feedback is crucial to understand their actions when they altered the baseline model. HoloArch provides material change options only textually, but the necessity of visual feedback aid was comprehended. In this issue, a participant stated:

> "Textures can be improved. There is no problem for architects if it is abstract. However, if this tool will also be used by other people, for example, an interior designer would want the haptic and visual feedback of that material." (P2)

As stated before, the provided object, material catalog, and design actions were found limited to perform some design actions. The missing action that oft-repeated by the participants was the unsupported opening element relocation action. As stated in the development process of the application, some of the reversible actions in the Revit side are not compatible with Unity's environment. Even though the location of the window can be changed theoretically in Unity, it is not possible to provide visually pleasant feedback to the users. For this reason, this action was discarded out in the development agenda. Even though this was an important action for daylighting design, because of the mentioned limitations, this was not included in HoloArch.

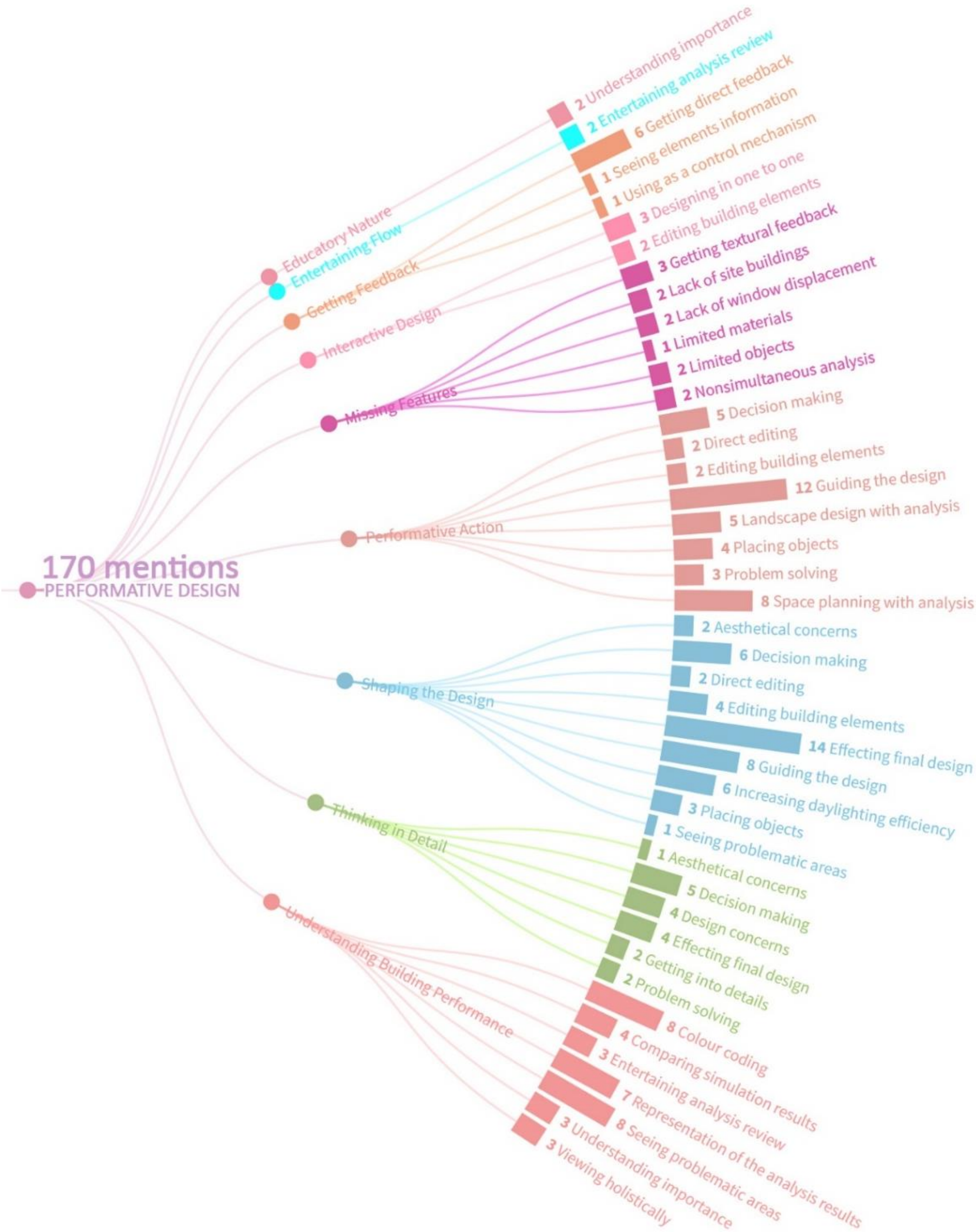


*Figure 5.21.* Breakdown of the Performative Design theme

Similarly, a non-simultaneous simulation visualization problem was stated once again as a lacking feature, but they were also aware of the second workshop that this problem was ongoing and cannot be changed in current conditions. A participant stated:

> "I guess non-simultaneous visualization of simulation is now a standard problem for HoloArch. I know this is not directly about your tool's deficiency. Instead, it is totally about the technologies at hand. But as a result, the current interventions were also effective for performative design."(P3)

In addition, some of the participants indicated that if the surrounding site buildings or a stereo panoramic image of the location had been provided to them, they could have performed the building orientation action more easily by taking that scenery as a reference. As future work, this feedback will be placed into focus.

**Understanding Building Performance and Thinking in Detail**

Understanding of a building daylighting performance was one of the major objectives of this thesis. According to feedback, HoloArch helped designers to understand complex daylighting simulation and to synthesize analyses results for performative daylighting design. Participants often expressed that they could realize how daylighting is an essential parameter for building design and its performance. HoloArch's interactive and understandable visualization of daylighting results was complimented often in the interviews. The colorful spheres represent daylight intensity, defined as "*entertaining*", "*guiding*", and "*informative*" in the interviews. Participants indicated that the color code used in spheres showed them the problematic areas straightforwardly, which allowed them to focus and to improve the daylighting performance in a particular space. They said that the red color-coded spheres had aroused a sense of warning in their minds, and provoked them to take into action to fix the illuminance problems. A participant asserted that:

> "It [daylighting analyses] gave me ideas about the daylighting condition of the building. It was like an advisor telling me what to do. I successfully interpreted it when I was designing and was able to see whether I improve." (P2)

The integration of the simulations in HoloArch, also gave the participants insights about future comfort and energy problems, along with the current daylighting conditions of the building. Since HoloArch is an immersive tool that enables users to experience their design on different scales, the participants stated that the tool allowed them to see every design flaws in detail. This led them to think more and detect problems before the realization of the final design. They propounded that the problems and details in the design of the building that was easily eluded in the plan or section views in conventional tools, but it became more visible for them via the aid of the IE. The participants indicated that solving the problems by instrumentalizing simulations would achieve them to design better-performing buildings. A participant explained how HoloArch helps designers in decision making by saying that:

> "I think that it will contribute to decision-making, create awareness, make better decisions, and gradually increase the performance of daylighting analysis to reach an optimum building performance." (P1)

**Performative Action and Shaping the Design**

HoloArch was developed as a tool that focuses on daylight design. Since the participants thought that all the actions provided are directly or indirectly related to the daylight performance, they were critical about every action they made. They tended to associate all the decisions to the building performance. The concentrated applications such as HoloArch can make it easier to give design decisions because of their singular simplistic approach. For example, if many performance-themed concepts such as structural and acoustic analysis would have come together in HoloArch, the participants might not be able to focus entirely on daylighting performance and might feel confused. About this focused approach, a participant said:

> "Okay, so you have passed a certain stage of the design, you have the primary outlines of the building, but thanks to HoloArch, you can still add shading elements, add trees that can solve the daylighting problems in a secondary intervention. So it's a good tool to focus on daylighting and increase its

> effective use after you have achieved a certain maturity level in your design." (P4)

As mentioned in previous chapters, HoloArch allows users to make various design actions related to daylighting. Even though the participants have tried HoloArch 2.0 before, they were impressed with the current design capabilities of HoloArch 3.0. The participants stated that they could fully understand what each action stands for and could functionalize these interrelated actions to redesign the baseline model's daylighting distribution. They decided between the performative actions according to their aesthetical tastes, problem-solving capabilities, and design decisions, since a lot of alternative design solutions were provided to them via HoloArch. During the experience, 3 out of 5 said that giving performative decisions in HoloArch was based on a trade-off between different architectural dynamics, including aesthetics, energy, comfort, glare, spatial qualities, and circulation. Moreover, they needed to think about everything holistically to be able to design a responsive building. Therefore it can be inferred that tools similar to HoloArch may lead designers to shape their designs by considering various architectural aspects of the building collectively. A participant summarized the tool's role in holistic performative approach:

> " ...I saw a lot of light coming from where I put the bed. Without such a tool [HoloArch], I would say "yes, perfect", but when I saw that how much light penetrated to the room, I shifted [it] to another place to prevent morning light that might disturb people...There are many design alternatives to solve the problem; for example, where I want to preserve aesthetical features of the window, I changed its material. If I didn't want to add some blinds in some places, I made the window smaller." (P5)

On the other hand, three of the participants said that HoloArch could help to make small but a variety of design decisions which then transforming to a considerable impact on the overall performance of the building. Many of the participants expressed that the tool encouraged them to achieve an effective daylighting design at the end of the experience. A participant added that the tool allowed her to find new connections in design and helped to experience the building like an end-user.

#### 5.10.5.3 Augmented Perception

This theme hosts both negative and positive categories and has a total of 154 mentions (*Figure 5.22*).

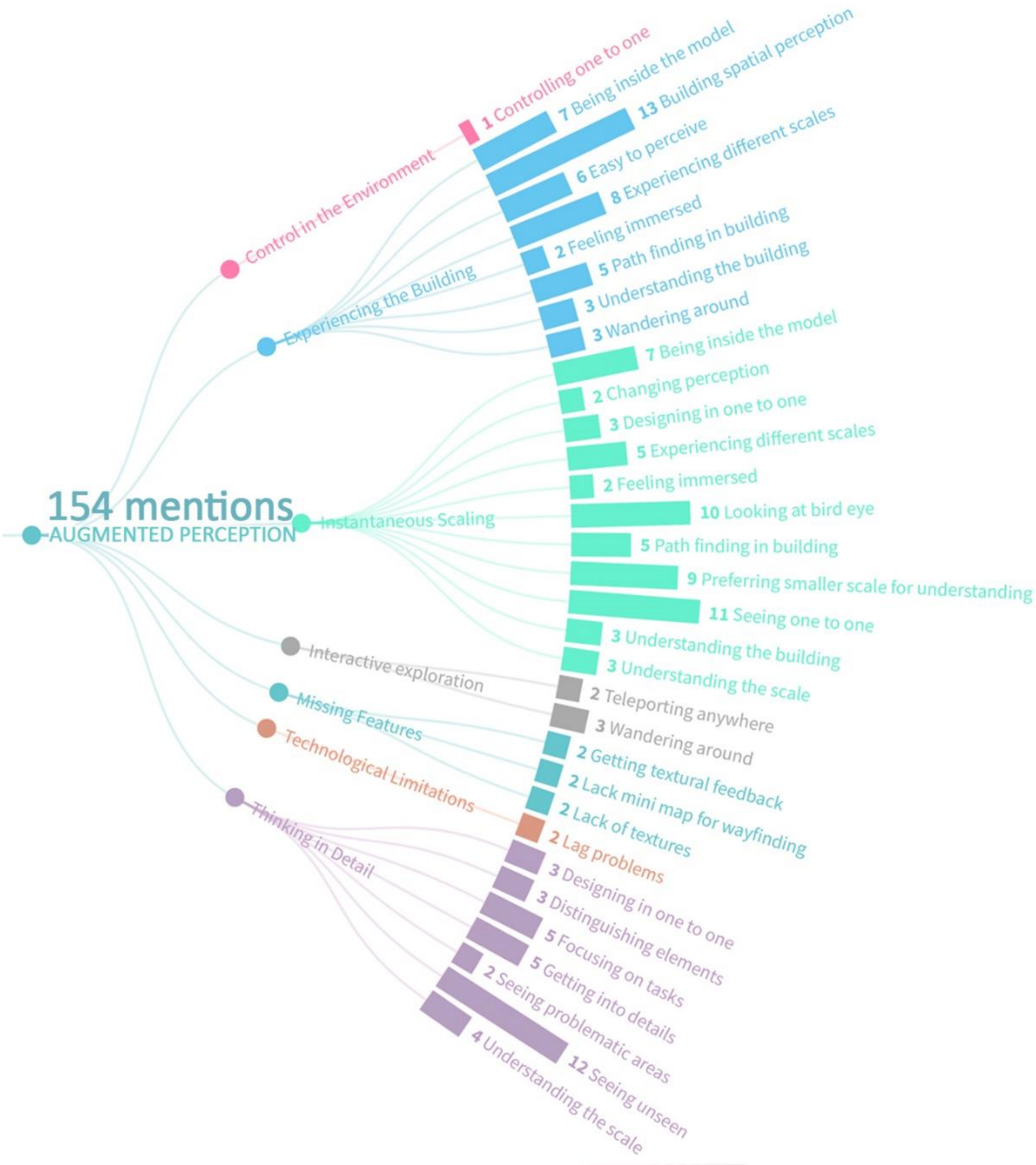


*Figure 5.22.* Breakdown of the Augmented Perception theme

**Adverse inhibitors: Missing Features and Technological Limitations**

The augmented perception theme was affected by lag problems. The used computer for the experience was not powerful enough to provide the visualization of a vast amount of colorful spheres together. This caused slight delays in the refresh rate of the display that might have a bad influence on the participants' perception. The missing features affected the perception theme emerged as lacking textures and absenteeism of the minimap. Two of the participants stated that during their exploration in the environment in 1/1 scale, they often had felt lost and had a hard time to find where they were. They proposed an additional minimap section on the UI to track their locations for solving this problem. This finding was unexpected and suggested that for immersive architectural applications, a minimap that represents where the avatar is standing in the environment is useful for navigation and pathfinding, especially on the 1/1 scale.

**Experiencing the Building, Interactive Exploration, and Instantaneous Scaling**

As a result of the interviews, interactively experiencing and exploration of the building led the participants to have an augmented perception of the environment. During the participant's first introduction to the system, all of the participants tended to wander around the building to understand the primary characteristics of the environment. They stated that teleporting in the 1/1 scaled environment allowed them to explore the building similar to an end-user. They added, the spatial qualities of the building became more visible but hard to comprehend the buildings as a whole on the 1/1 scale. For this problem, the participants functionalized the scale feature where they could manage to switch back in forth between different scale options. According to the feedback, each scale option offered different experiences to them;

while the smaller scales (e.g., 1/5) were found appropriate to understand the main organization of the site, the larger scales (e.g., 1/1) were decided for capturing the spatial details of spaces. Two of the participants stated that being inside the model in 1/1 scale was "immersive", "fun", and "expressive". Since HoloArch enables designing in different scales, three of the participants stated that designing performatively in IE offered something they had never experienced before. They claimed that the spatial qualities of spaces were more apparently perceived via HoloArch, and this visibility had a significant impact on their design activity. Regarding this, a participant said:

> "I think HoloArch is an additional tool that completes the design experience with its augmented perception capabilities. You can design in different scales easily to see your design at various perspectives...all of them happen in a blink that is something conventional computer display cannot provide, and it [augmented perception] allows you to think differently." (P3)

On the other hand, the visualization of the building played a significant role in the perception of the building. HoloArch presents an isolated abstract environment for designers to focus on the performative design actions affecting the architecture of buildings only. The abstract visualization approach applied in HoloArch caused confrontational arguments in the interviews. Even though some of the participants were found abstract visualization as nondistracting; a few of them were persistent about the photo-realistic textures. This difference of between the opinions could be stated by giving some direct quotes from the participants:

> "I was more comfortable focused on what I wanted to do in HoloArch. If it [the environment] would be realistic, I would probably stick to other details and digress from daylighting design." (P2)

> "I think the materials had to be presented in order to see glare problems." (P3)

In this regard, the findings showed that there was a matter of negotiation in terms of building visualization. Even though all of the participants were architects and architecture curriculum commonly involves abstraction, the realistic visualization was found crucial for the performative design by some participants. This could be solved by providing two different switchable options for realistic and abstract visualization of the environment. In this way, participants could work with which visualization type they desire.

These findings will doubtless be much scrutinized, but there are some immediately dependable. The tools similar to HoloArch hold potential for designers to understand architectural models by scaling, to explore them by walking inside and these leading an augmented perception in terms of design activities. In this regard, the findings have similarities in the literature.

### Thinking in Detail

According to the findings, the perks of augmented perception in HoloArch is mainly based on the ground of "seeing the unseen" code. The participants often repeated this code when the remarks on perception were asked about. As a consequence of the provided instant scaling and immersion, the participants had the chance to experience the building on its real scale. According to the responses, being inside the model was found useful that enabled them to see the details which were not easily noticeable in the plan or section drawings. By seeing the things they had never thought before, led them to think more about their design decisions. The overthought design decisions effected shaping their daylighting and architectural designs. The participants stated that space planning when they were inside the building was more insightful and adequate because they could experience the design events happening around them at the first-person view. In parallel, the visualization of the simulation results was found successful in terms of perception. With the augmented perception for interpreting the simulations, the participants stated that the spheres allowed them to detect problematic spaces more smoothly. Relatedly, a participant stated that:

> "The spheres did not distract me. They did not seem to belong to the building. In other words, it was apparent that they spoke in a different language, they were different from the building and they were there in terms of representation. If the simulations were represented as boxes, they could have been confused with building elements. I think spheres make it easier to understand and it was nice to show the illuminance density topographically, and it was nice to be surrounded them as well." (P5)

It can be concluded that HoloArch augmented the spatial perception of designers and this potential resulted in them to see the problematic spots, the details and the spatial qualities of the spaces.

#### 5.10.5.4 Interaction

This theme hosts both negative and positive categories and has a total of 154 mentions (*Figure 5.23*)

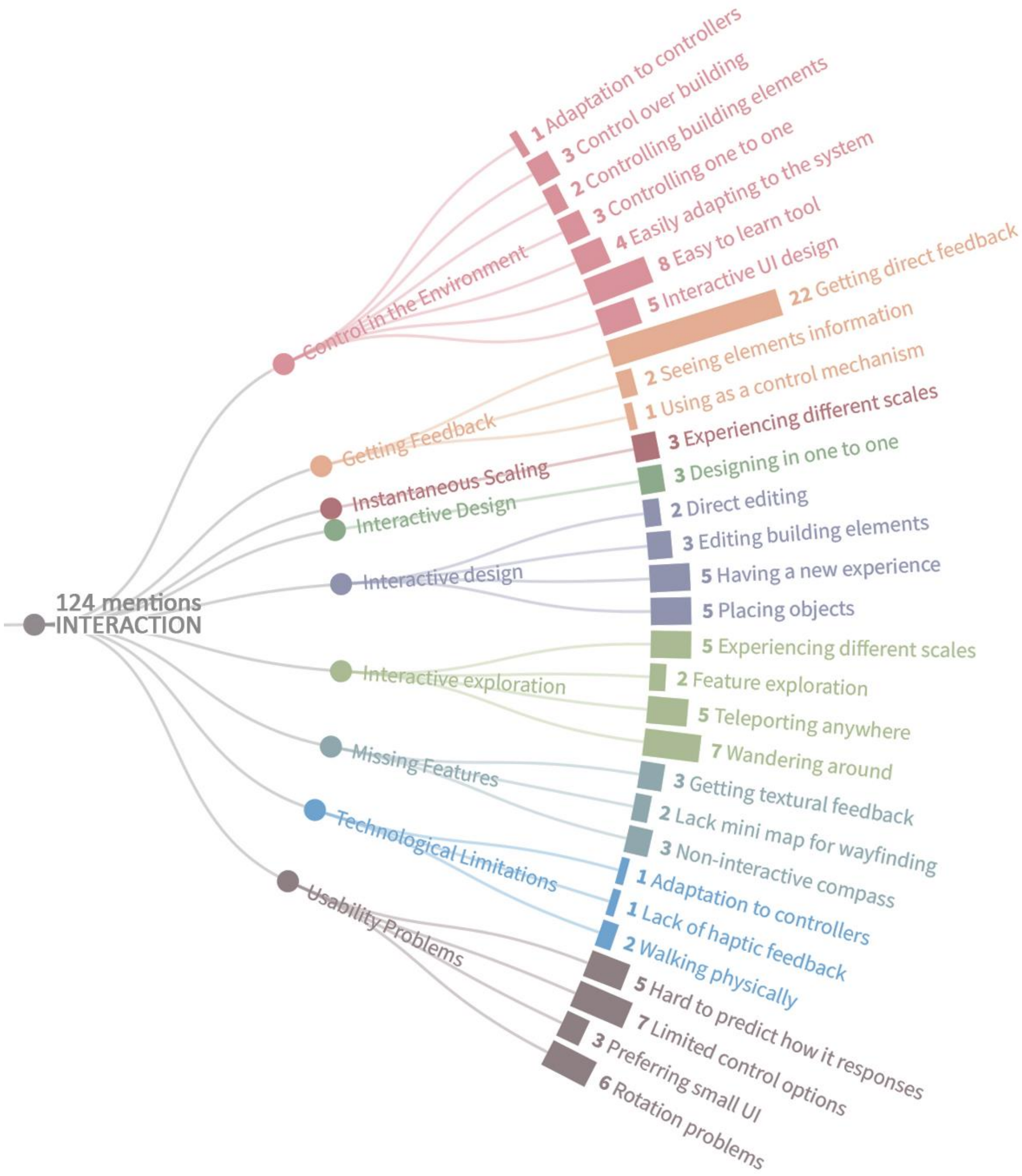


*Figure 5.23.* Breakdown of the Interaction theme

**Adverse inhibitors: Usability problems, Missing Features, and Technological Limitations**

The main flaws of HoloArch emerged under this theme. The inhibitors affected the user interaction arose from the usability problems, technological limitations and the missing features of the tool. Similar to previously explained missing features, the limited provided objects, the lack of visual feedback in texture changes, and minimap absenteeism were the main missing part of the interaction theme. For the technological limitations, the participants wished that haptic feedback and walking physically in the environment could be possible. In addition, a participant had a hard time to adapt to the controllers, but these problems are rooted in external indicators. The main problems directly related to HoloArch were the usability issues detected in the interviews. Many of the participants stated that the tool was controlled similar to computers and wished that more gestural interaction methods could be defined. Some of them found UI too big, which sometimes obstructed to interact with the model. The most problematic action was found in the rotation command. The participants indicated that which direction the object would be rotated was hard to predict beforehand. The increment rotation buttons were also not found useful by some of the participants. The reason for that could be the marginal differences between the provided angles, which led to difficulties in aligning particular objects. Although some usability problems still exist in HoloArch 3.0, the participants aware that the tool has been improved substantially in terms of usability issues since HoloArch 2.0. In addition, Except for one participant, the others had no discomfort problems during the experience and this led them to perform interactive actions without any disruptive effect.

**Control in the Environment**

One of the primary parent categories constitutes the interaction theme was the control in the environment. Participants often stated that the usability was simplified and facilitated compared to conventional design tools. The protocol followed at the beginning of the experience has played an active role in participants' learning how to use HoloArch. The ease of use and learning provided has enabled the participants to perform their actions with relative ease. This easy to learn and use aspect of HoloArch could be explained the new UI design of the tool. The new one was found successful in terms of visual and functional quality. With the provided logos that represent the actions, the participants have intuitively found the operations they wanted to use. Also, these developments in HoloArch 3.0 influenced on the controlling building elements and the environment. A participant compared different versions of HoloArch and stated that with new HoloArch, she understood that the control in the environment could play a remarkable role in affecting the interaction and usability of the immersive tools.

**Interactive Design and Getting Feedback**

The most recurring code that affects the interaction theme in the transcriptions was revealed as "*getting feedback*". The provided feedback in HoloArch can be classified as visual (e.g., changing the size of a window), and textual (e.g., BIM Data of the selected elements) which are provided via different actions. The missing textural feedback was found necessary for the interaction theme and planned to be added as future work to the development agenda. Three of the participants expressed that they preferred to perform actions which gave direct visual feedback to them, rather than the "*stagnant*" textual data. However, they could also functionalize the static text-based data as a control mechanism. They said that they could compensate for the deficiencies caused by the lack of textural feedback from textual feedback. A participant's experience can be an example to support this claim; she said:

> "Since there are no textures provided, seeing the materials of the elements in the BIM data tab allows you to have an idea about them. For example, I have changed reflectivity of the glazing, even if I do not see the data of it visually, it was precious to be able to see the material specifications in the tab." (P2)

The visualization of BIM data allowed participants to get informed about the properties of the building elements. They functionalize this feature to control whether their actions were appropriately facilitated or not. The provided interaction methods found enough them to perform design actions. A participant summarized the influence of direct feedback to an interactive design by saying that:

> "You change the objects and building elements directly by seeing and living. Importantly, you can see the result of your design and manipulation interactively with the provided feedback. This interaction is an important aspect that immersive environments present." (P5)

# CHAPTER 6

# CONCLUSION

The conducted literature review revealed that performative simulation tools, particularly daylighting, are an essential concept in architectural design, but its assessment can be complicated. The use of BIM tools is identified as the critical solution for performance-based architectural design with its integrated simulation tools, but both BIM and simulation tools are visualized through non-immersive computer displays. On the other hand, IE can create a multi-sensory, first-person view, three-dimensional environments. Moreover, IE holds an unfulfilled potential in terms of the implementation of interactive performative and architectural design. In this regard, an integrated tool focusing on expanding capabilities of BIM, integrating daylighting simulations into design processes, and testing architectural design possibilities in immersive environments was developed as a case study to be able to answer this thesis' research questions. A responsive and interactive tool named HoloArch was proposed in order to be a solution to the existing problems in the mentioned specific fields of architecture. HoloArch was the outcome of a collaborative fully-funded research project between METU's Department of Architecture and Multimedia Informatics Program with the contributions of Assoc. Prof. Dr. İpek Gürsel Dino, Assist. Prof. Dr. Elif Sürer and M.Sc. Oğuzcan Ergün.

The selection of daylighting simulations shaped and contributed the framework of HoloArch to be a more versatile tool where various performative design actions can be facilitated visually, interactively, and these actions results can give immediate and visual feedback to the users. Autodesk Revit was selected as the base BIM environment of HoloArch for its integrated performative assessment tools, its extensive audience coverage, and data workflow capabilities. HoloArch was designed to serve both virtual and mixed reality environments. Since these distinct environments offer unique experiences to their users, both of the systems were added to the development agenda of HoloArch. HoloArch used Autodesk Revit as a base BIM environment, concentrated on the performative daylighting design of the buildings, and was developed for HTC Vive and Microsoft HoloLens users to provide VR and MR experiences by using Unity game engine. The HoloArch project was initiated as an ever-growing and evolving system throughout the development process. The creation, improvement, planning, evaluation, and design of the system were interconnected and these stages were grown and expanded by depending on each other. The environment allowed users to interact, edit, visualize, manipulate, and review architectural models and to perform daylighting design in immersive environments. In contrast with the existing immersive tools in architecture, HoloArch offered continuous bidirectional workflow between BIM tools and game engines. Its iterative export-import processes enabled the designers to work in different design environments without data loss. HoloArch had three versions with different features, and these versions' UX studies were conducted in different events.

The first UX study was tested with 9 participants in a 2,5-day international workshop at the University of Lisbon as a part of DCG Summer School 2018 via HoloArch 1.0. As preliminary findings from the study, the MR environments have accomplished to guide architectural design processes and to augment the perception of the complex daylighting simulations results. HoloArch 1.0 was an integrated visualization tool, which supported the visual perception of both architectural models and daylighting simulations by using HoloLens. The primary outcomes of the study indicated that MR-based performative visualizations had the potential to improve visual perception and model interaction of the BIM models and these potentials led designers to understand the role of performative daylighting simulations in architectural design. In conclusion, the results of the questionnaire and the user comments validated the potential of the system. In particular, the tool's visualization capabilities were found more successful than the conventional Revit environment in terms of visual perception, navigation through the model and the visualization of integrated simulation data. Even though participants faced problems during the experience, overall results were higher than expected. This might be related to the participants' initial excitement when they used new and expensive technology. They showed a higher level of curiosity and engagement to the technology so they might have omitted some of the limitations of the MR.

The second UX study was carried out in a 2 days national workshop at the METU Faculty of Architecture with 21 participants via HoloArch 2.0. HoloArch 2.0's UX study also addressed a comparative study that examined how different IE types could affect participants' visual perception and model interaction experiences. Data acquisition was made with both open-ended interviews and written feedback of the participants at the end of the workshop. Collected data were categorized according to the most mentioned themes and was discussed under two categories: HoloArch's affordance for the architects and MR-VR comparison in terms of visual perception and model interaction. According to user feedback, HoloArch 2.0 has potentials in terms of daylighting analysis visualization, interactive performative design, easy adaptation, and usability. In contrast, HoloArch 2.0 has limitations in terms of unsatisfactory BIM data visualization, absence of simultaneous daylighting analysis update, and UI design. The UX study showed that user experiences could be differed according to the working principles of the IE. In this regard, the majority of the participants in both of the comparative studies (model interaction, visual perception) found that the VR environment was more suitable for the tools similar to HoloArch 2.0.

Lastly, HoloArch 3.0's UX study was performed in a user study with 5 participants at the METU Faculty of Architecture. Different from the other Ux studies, more planned and comprehensive data collection and analysis methods were adapted to reveal every possible potential of the tool. According to the feedback, while HoloArch's most prominent strengths were found as; "*Integration of Different Concepts*", "*Instantaneous Scaling*" and "*Bidirectional Workflow*", the most pronounced weaknesses found as; "*Non-simultaneous Simulation*", "*Usability Problems*" and "*Control and Navigation*." Moreover, HoloArch was found as "*excellent*" in terms of its usability. HoloArch 3.0 was performed well in the TAM and presence questionnaires with marginal differences from the threshold levels.

When the participants' final designs were re-simulated and compared with the baseline building, it was revealed that all of them improved and altered the daylighting performance of the baseline building effectively. The interview results were indicated that HoloArch 3.0 was a supportive tool in terms of augmented perception, continuous design processes, performative daylighting design, and interaction.

In conclusion, according to the outcomes of the case study, IE holds high potentials where performative design actions can be taken place interactively and simultaneously. These environments may guide designers to achieve practical solutions for performative architecture and to understand the importance of the performative simulations on architectural design. IE augments provide designer's perception, which may lead them to think in more detail, and to see the problematic areas, to understand the spatial qualities of spaces. The integration of different design concepts in a single tool helps designers to think various design aspects interrelatedly and to bridge the gap between the misconnections between concepts. In addition, these integrated environments play a significant role in the education of novice designers. A reversible workflow across platforms strengthens the design processes and leads designers to achieve the final design more smoothly and efficiently. As a subjective ending remark of the author, the HoloArch project was an accomplished example that offers a lot of novel approaches and contributes to the literature by pointing out the abovementioned aspects. The conducted user studies show that HoloArch plays a significant role in performative design enhancements when a certain maturity level achieved in designs. The conducted user studies show that HoloArch plays a significant role in performative design enhancements. Even though performative design decisions are a vital part of the early design stages, HoloArch can also improve the performance of buildings achieved in certain design maturity. However, more studies should be performed to investigate other possibilities of these tools.

## 6.1 Limitations of the Study

Several limitations in this thesis needed to be acknowledged. The problems encountered in the thesis have led to a limitation of the scope of HoloArch. Firstly, the time was allocated for the project was restrictive for HoloArch to achieve a certain maturity level to be used professionally in architectural practices. In less than two years, the tool's main outlines, requirements, and the concepts were identified, the tool was developed from nothing, three versions of the tool was tested in user studies including national and international events, three papers were published and presented. This intense time schedule undoubtfully limited HoloArch to reach its full potential since there was a small group of people in the development team.

Secondly, the data transaction and compatibility problems between diverse platforms decelerated the development process of HoloArch. Almost forty percent of the time was devoted to solve the data transaction methods and establish a bidirectional workflow for HoloArch. If more time were available, a more straightforward and automatic workflow could have been established for HoloArch. Moreover, the compatibility problems limited the performative actions that HoloArch provided to users since some of the actions in Unity do not have a correspondence in the Revit environment. In addition, the simultaneous update of the daylighting simulations in HoloArch has not been able to be accomplished since the complex daylighting calculations exceed the knowledge of the developers. If more time had been allocated for fixing this problem, HoloArch could have been a more powerful tool in terms of performative design and interaction capabilities.

The generalisability of these results is subject to certain limitations. One of the other limitations of this study was that the numbers of participants were relatively small since finding people who had a background in the wide range of concepts was not easy. In this regard, several workshops were performed to teach the participants about the specific subjects that HoloArch tackles, and then they were asked to participate in the UX studies. In this way, possible adaptation problems were solved. However, the bigger sample size would have been more effective in generalizing the results. This limitation means that study findings need to be interpreted cautiously. Lastly, according to the feedback obtained from the participants, the existence of certain biological and technological limitations at the present time conditions was pointed out. In this regard, it can be said that people may need more time to adapt and use systems like HoloArch in their professional practices.

## 6.2 Suggestions for Further Studies

According to the feedback, the participants expressed that the IE was an excellent solution to comprehend and understand complex performative simulations and should not be applied only for daylighting but also for wind, energy, and similar simulation types as well. In addition, HoloArch holds an educative potential to teach the importance of daylighting in building design. Further research may be done to investigate implementing other types of performative dynamics of the building assessment into immersive design environments for the educative purposes of the novice designers. Moreover, along with the current capabilities of HoloArch, other performance-related simulations and design actions may be possible to be integrated for further studies.

According to the feedback, the participants stated that HoloArch 3.0 would have helped to design more effective daylighting solutions for buildings. In fact, without a controlled experiment between conventional design environments and HoloArch, this claim cannot be proved. For understanding whether the tools similar to HoloArch may aid designers to design of better-performing buildings in terms of daylighting or not, a comparative study with control groups should be conducted.

HoloArch can visualize different daylighting simulations comparatively and effectively, but users have to wait for the impacts of the performed design actions on the simulations. A further study with more focus on the integration of the simultaneous daylighting simulations update is therefore suggested, and more research on this topic needs to be undertaken before the association between performative simulations and design in immersive environments is more clearly understood.

Considerably more work should need to be done with bigger sample sizes to increase the reliability of the findings and the possibility of generalization of the thesis outcomes for other immersive tools similar to HoloArch. This research has thrown up many questions in need of further investigation. More research is required to determine the efficacy of MR with newly introduced Microsoft HoloLens 2. The problems indicated in the UX studies might be solved with this new technology. In this way, the MR environments' usability and adaptation problems may be no longer a limitation, and MR environments may be found more appropriate instead of VR by the participants.

As mentioned in several papers[169], IE promotes collaborative design processes. HoloArch may propose a collaborative environment where people from different professions and backgrounds can work together and understand each other. These systems are likely to be implemented and used by the construction industry in order to increase communication between building stakeholders. For this reason, this collaborative aspect of these integrated environments, similar to HoloArch should be investigated in further studies as a final recommendation.

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# APPENDICES

## A. Presence Questionnaire

| Presence Questionnaire (19 Questions, Answers from 1 to 7, 1 is the most negative) | |
|---|---|
| Realism | 1. How natural did your interactions with the environment seem?<br>2. How much did the visual aspects of the environment involve you?<br>3. How natural was the mechanism which controlled movement through the environment?<br>4. How compelling was your sense of objects moving through space?<br>5. How much did your experiences in the virtual environment seem consistent with your real-world experiences?<br>6. How compelling was your sense of moving around inside the virtual environment?<br>7. How involved were you in the virtual environment experience? |
| Self Evaluation of Performance | 8. How quickly did you adjust to the virtual environment experience?<br>9. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience? |
| Possibility to Act | 10. How much were you able to control events?<br>11. How responsive was the environment to actions that you initiated (or performed)?<br>12. Were you able to anticipate what would happen next in response to the actions that you performed?<br>13. How completely were you able to actively survey or search the environment using vision? |
| Possibility to Examine | 14. How closely were you able to examine objects?<br>15. How well could you examine objects from multiple viewpoints?<br>16. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities? |
| Quality of Interface | 17. How much delay did you experience between your actions and expected outcomes?<br>18. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?<br>19. How much did the control devices interfere with the performance of assigned tasks or with other activities? |

## B. TAM Questionnaire

| Technology Acceptance Model (13 Questions, Answers from 1 to 10, 1 is the most negative) | |
| --- | --- |
| Perceived Ease of Use | 1. I liked training with the HTC Vive and controllers.<br>2. During the interaction using HTC Vice, I felt pain and/or discomfort.<br>3. It's easy to interact with the environment.<br>4. The UI reacts readily to my movements.<br>5. I did not find it hard to interact with the virtual world.<br>6. I found the graphical interface clear and explanatory.<br>7. The instructions of the UI are clear. I understood what to do in the UI and how.<br>8. The visual signals that appear when I click a button are useful.<br>9. The virtual headset is big and close enough. |
| Personal Enjoyment | 10. The environment was challenging and fun.<br>11. I liked the interface design. |
| Behavioral Intention | 12. I would like to keep using this system in the future.<br>13. If I had the option to keep using the system at home, I would use it often using HTC Vive and controllers. |

## C. SUS Questionnaire

| System Usability Scale (10 Questions, Answers from 1 to 5, 1 is the most negative) | |
|---|---|
| SUS | 1. I think that I would like to use this system frequently.<br>2. I found the system unnecessarily complex.<br>3. I thought the system was easy to use.<br>4. I think that I would need the support of a technical person to be able to use this system.<br>5. I found the various functions in this system were well integrated.<br>6. I thought there was too much inconsistency in this system.<br>7. I would imagine that most people would learn to use this system very quickly.<br>8. I found the system very cumbersome to use.<br>9. I felt very confident using the system.<br>10. I needed to learn a lot of things before I could get going with this system. |

## D. Consent Form (Turkish)

**ARAŞTIRMAYA GÖNÜLLÜ KATILIM FORMU**

Bu çalışma, Dr. Öğr. Üyesi İpek Gürsel Dino, Dr. Öğr. Üyesi Elif Sürer ve Şahin Akın tarafından tasarlanıp METU: Immersive and responsive environments çalıştayında yürütülecek bir çalışmadır. Bu form sizi araştırma koşulları hakkında bilgilendirmek için hazırlanmıştır.

**Çalışmanın Amacı Nedir?**

Önerilen araştırma projesi, sanal ortamların sürdürülebilir mimari tasarım süreçlerinde kullanılması için yöntem ve araçlar geliştirmeyi amaçlar. Bunun için bina bilgi modelleme (Building Information modeling veya BIM) araçlarının semantik olarak zenginlertirilmiş veri ortamından ve bina enerji simülasyon araçlarının performans hesaplama ve sayısallaştırma işlevlerinden yararlanarak, bunların sanal ortama aktarılması ve kesintisiz olarak sanal tasarım aktivitesine entegre edilmesini amaçlar. Görsel algının artırıldığı sanal ortamlar, aynı zamanda sürdürülebilir bina tasarımında kritik rol oynayan performans verilerinin 3 boyutlu görselleştirilmesi açısından da büyük potansiyele sahiptir. Önerilen çalışmada geliştirilecek sistemin, sürdürülebilir binaların bilinçli ve efektif tasarımında tasarımcıya destek sağlaması amaçlanmıştır. Belirtilen araştırmada geliştirilen karma gerçeklik sistemi ODTÜ'de yapılacak ve araştırmacılar tarafından düzenlenecek bir çalıştayda uygulanacaktır. Öğrencilerden, sürdürülebilir tasarım süreçlerinde bu sistemi kullanmaları istenecek, ve bu süreç sonunda öğrencilerden bazı anketleri doldurmaları ve sistem hakkında geri bildirim vermeleri istenecektir. Bu geri bildirim ile, geliştirilmiş sistemin validasyonu gerçekleştirilecektir.

**Bize Nasıl Yardımcı Olmanızı İsteyeceğiz?**

Sizden yaratılan ortamla etkileşmenizi ve sonrasında da tasarımla ilgili anketlerimizi doldurmanızı isteyeceğiz.

**Sizden Topladığımız Bilgileri Nasıl Kullanacağız?**

Çalışmada sizden kimlik belirleyici hiçbir bilgi istenmemektedir. Ede edilen veriler tamamen gizli tutulacak ve sadece araştırmacılar tarafından değerlendirilecektir; elde edilecek bilgiler bilimsel yayımlarda kullanılacaktır.

**Katılımınızla ilgili bilmeniz gerekenler:**

Bu çalışma, kişisel rahatsızlık verecek uygulamalar içermemektedir. Ancak, katılım sırasında herhangi bir nedenden ötürü kendinizi rahatsız hissederseniz çalışmaya katılımınızı yarıda bırakıp çıkmakta serbestsiniz. Böyle bir durumda bu çalışmayı tamamlamadığınızı söylemek yeterli olacaktır. Bu çalışmaya katıldığınız için şimdiden teşekkür ederiz.

**Araştırmayla ilgili daha fazla bilgi almak isterseniz:**

Çalışma hakkında daha fazla bilgi almak için Dr. Öğr. Üyesi İpek Gürsel Dino (E-posta: ipekg@metu.edu.tr), Dr. Öğr. Üyesi Elif Sürer (E-posta: elifs@metu.edu.tr) ve Şahin Akın (E-posta: shnkn@hotmail.com ) ile iletişim kurabilirsiniz.

***Yukarıdaki bilgileri okudum ve bu çalışmaya tamamen gönüllü olarak katılıyorum.***

(Formu doldurup imzaladıktan sonra uygulayıcıya geri veriniz).

İsim Soyad Tarih İmza