M.Des Project 3

Collaborative Mixed Reality ecosystem for AEC Industry

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2 Introduction

Collaboration is a “synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem.” (Roschelle and Teasley, 1995) [17]. In more simpler terms when two or more people work or attempt to work together to solve a problem can be considered as collaboration. Humans have been working together collaboratively for ages to get better output and results. It happens by construction, sharing and repairing of shared knowledge.

Computers are increasingly used to enhance the collaboration between people. Collaborative tools have become common and are being used in different sectors for different kinds of collaborations. With the development of such tools, the Human-Computer Interface is further evolving into Human-Human Interface mediated by computers. The tools for three-dimensional CSCW (Computer Supported Collaborative Work) are still rare. Technologies like VR/AR/MR may help overcome these limitations [2].

Mixed reality (MR) environments are defined by Paul Milgram in which elements of the real and virtual world are merged on a single display[14,20]. There are a lot of mixed reality based single and multiple user applications available now. Different augmented reality technologies are available today to experience these applications.

Research has shown that Mixed Reality interfaces can aid a person to interact with the real world objects in ways never before possible[3]. This project aims at designing a collaborative platform for AEC industry through mixed reality by using HMD’s for enhancing collaboration, coordination, and comprehension between different groups of collaborators.

2.1 Context

Architectural projects involve a multidisciplinary collaboration and exchange of large building data sets. Architectural projects typically are the projects in which a large number of stakeholders such as the owner, architect, consultants, main contractor, subcontractors and suppliers work together in all the stages, i.e., design, construction, and maintenance. All these stakeholders work together in agreement with shared goals and find solutions that are satisfying to all concerned.

In architectural practice, the traditional way of collaborating is by exchange of 2D drawings. The data is exchanged or shared either electronically (email or cloud storage) or by sending physical sheets to the concerned stakeholders. During the design and construction process, the data is revised many times. Each team needs to keep track of the revisions and the current document which is being circulated among all the stakeholders.

As the building forms and structures are becoming more complex, 3D models are being used widely (digital or physical) for better comprehension when working with other teams. With the introduction and adoption of advanced CAD tools like BIM, the data is now being exchanged electronically in the form of digital 3D models with contains both geometric as well as non-geometric data.

2.2 Opportunity Space

AEC projects involve a lot of meetings between the stakeholders. These meetings are held on the site or at some office space. Not always the collaborators are present in the same area or close vicinity, which makes travel compulsory for such meetings.

BIM allows collaboration among different stakeholders by introducing a common platform to work. Though the data exchange is done in the form digital 3D models of the building/structure, the full potential of 3D is not being utilized as the 3D data is being viewed on a flat screen. Also, as the data is limited to flat screens, it does not allow the user to comprehend the information in context to the real environment on 1:1 scale. We find an opportunity space where we can make people collaborate using the full potential of 3D data and providing them an experience of co-located collaboration using mixed reality.

2.3 Objectives

The project aims at identifying and designing interactions and activities for enhancing the collaboration between multiple stakeholders at different stages of an architectural project.

The enhancement would be in terms of better workability, better comprehension of 3D data and allow the user to relate the content with the real environment and improve decision-making ability.

2.4 Scope

The project would consist of studying and analyzing the nature of collaborations that happen during an architectural project. Based on the secondary and primary research, scenarios as per our context would be identified and those scenarios would be designed for enhancing collaboration using mixed reality. The aim is to develop an ecosystem which can fit into architectural processes easily.

3 Literature Review

This section consists the literature review of various topics mentioned below:

3.1 Collaboration and Collaborative Working

Collaboration is a “synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem.”[13,17]. In more simpler terms when two or more people work or attempt to work together to solve a problem is known as collaboration.

The terms collaboration and cooperation at times are used interchangeably, but they represent fundamentally different ways of contributing to a group, and each comes with its dynamics and power structures that shape groups in different ways.

When collaborating, people work together (co-labor) on a single shared goal. Whereas, when cooperating, people perform together while working on selfish yet common goals. In architectural projects all the collaborators work on a shared goal, so the project is based on collaboration rather than cooperation.

Collaboration can be described by the dimension of its openness and governance[15]. These can be further classified as:

Fig. 3.1
Collaborative Working

Openness of collaboration

1. Open Collaboration
    - Open for everyone to take part
    - The subject area is not well defined
    - Problem is published publicly
    - A large number of contributors

2. Closed Collaboration
    - A manager or group of people chooses participants
    - Small/ limited number of contributors
    - The problem area is well defined
    - Appropriate contributors are known

Governance of collaboration

1. Flat Collaboration
    - All participants can take part in the decision-making process.
    - All participants make the decision together
    - All participants agree on the goals of the project

2. Hierarchical Collaboration
    - A selected participant or organization is in charge of decision making
    - Tasks are distributed among the participants
    - Participants can have their own goals within the hierarchy

Collaborative projects combine different modes to achieve the desired goal [15].

1. Open and Hierarchical
Anyone can contribute, but the person, company or organization in charge of the project decides which ideas or solutions to develop.

2. Open and Flat
There is not an authority who determines which innovations will be taken further-because anyone can contribute to the process and use delivered results.

3. Closed and Hierarchical
The participants have been chosen by the authority who also decides which ideas will be selected and developed.

4. Closed and Flat
The group of participants selected by an authority share ideas and make the decisions and contribution together.

These modes allow for an understanding the kinds of collaboration and getting a bigger picture of how things work.

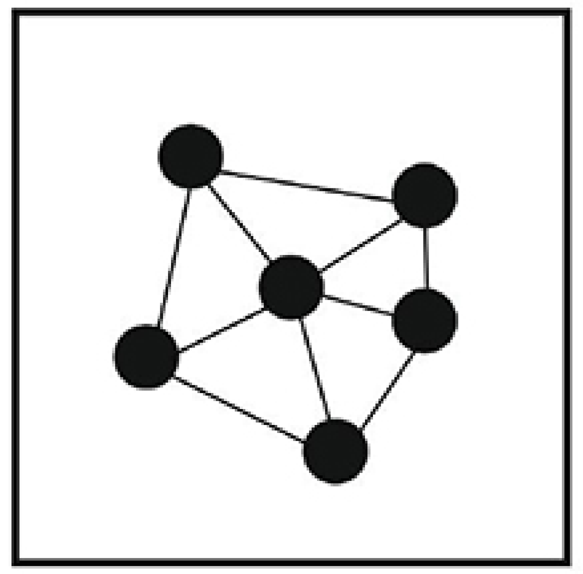

Fig. 3.2
Dots representing people collaborating in a co-located space (Local Collaboration)

Type of Collaborations - Space and Time

By the physical location of the collaborators, collaboration can be of two types, Local and Remote Collaboration. Local collaboration occurs in a co-located space where all the collaborators are present at the same physical location. Remote collaboration is when at least one of the collaborator is present at a geographically different location.

By the time of the activity, collaboration can be of two types, Synchronous, and asynchronous collaboration.

Synchronous activities are carried out at the same time by all the collaborators whereas asynchronous activities are carried out at different times by different collaborators.

For collaborative working in the given scenarios communication among the collaborators play a vital role. The following section touches upon the role and importance of communication in collaborative working.

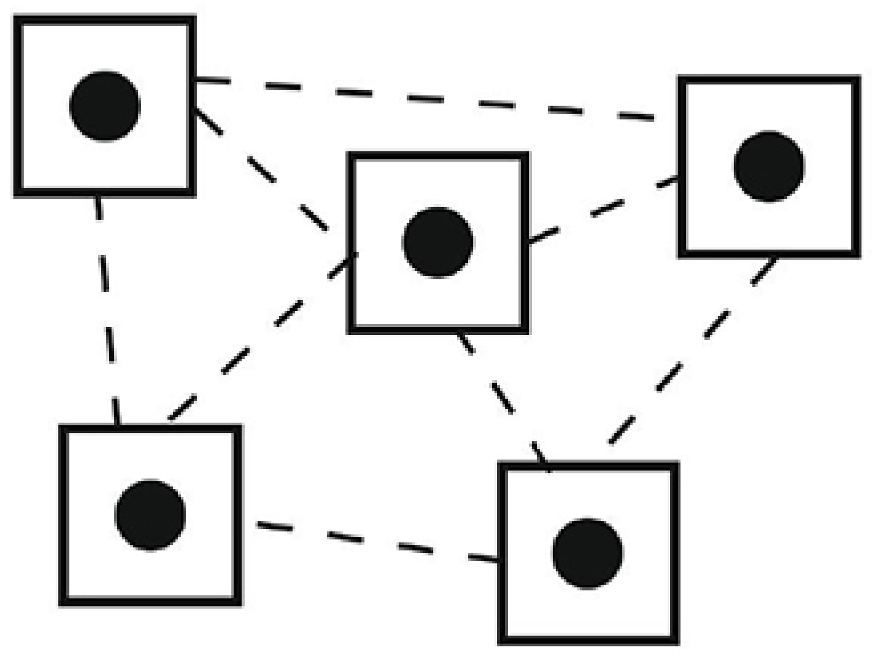

Fig. 3.3:
Dots representing people collaborating in separate spaces (Remote Collaboration)

Role of communication in collaborative working

In 1960’s Ervin Goffman, a sociologist described communication as a system of intentional and unintentional expressions [8].

Intentional expressions are like speaking, eye contact, etc. which we make while we interact with others. Unintentional expressions are made up of non-verbal cues in our body language. Intentional and unintentional expressions are essential when we collaborate.

The introduction of telephone facilitated the communication by augmenting our voice. We try to replace the visual cues with audio. The inflection of words, the pace of speech and pause for responses are some of the acts over the telephone.

Video conferencing took it further. Visuals enhance both intentional and unintentional expressions of the speaker and listener: Gauzing reactions, showing our surroundings, presenting things. 2D video struggles to mimic the presence and immersion of being in a conversation. The video lacks the ability to communicate intentional and unintentional expressions fully. And that limitation is one of the critical reasons why travel remains a crucial part of business today.

In 1980’s people started using computers for collaborative working which triggered the emergence of CSCW as a field. Now we know how we collaborate and what are the types of collaborations, the following section is a literature review of CSCW as the project is about collaboration using computers.

Fig. 3.4:
Intentional Expressions

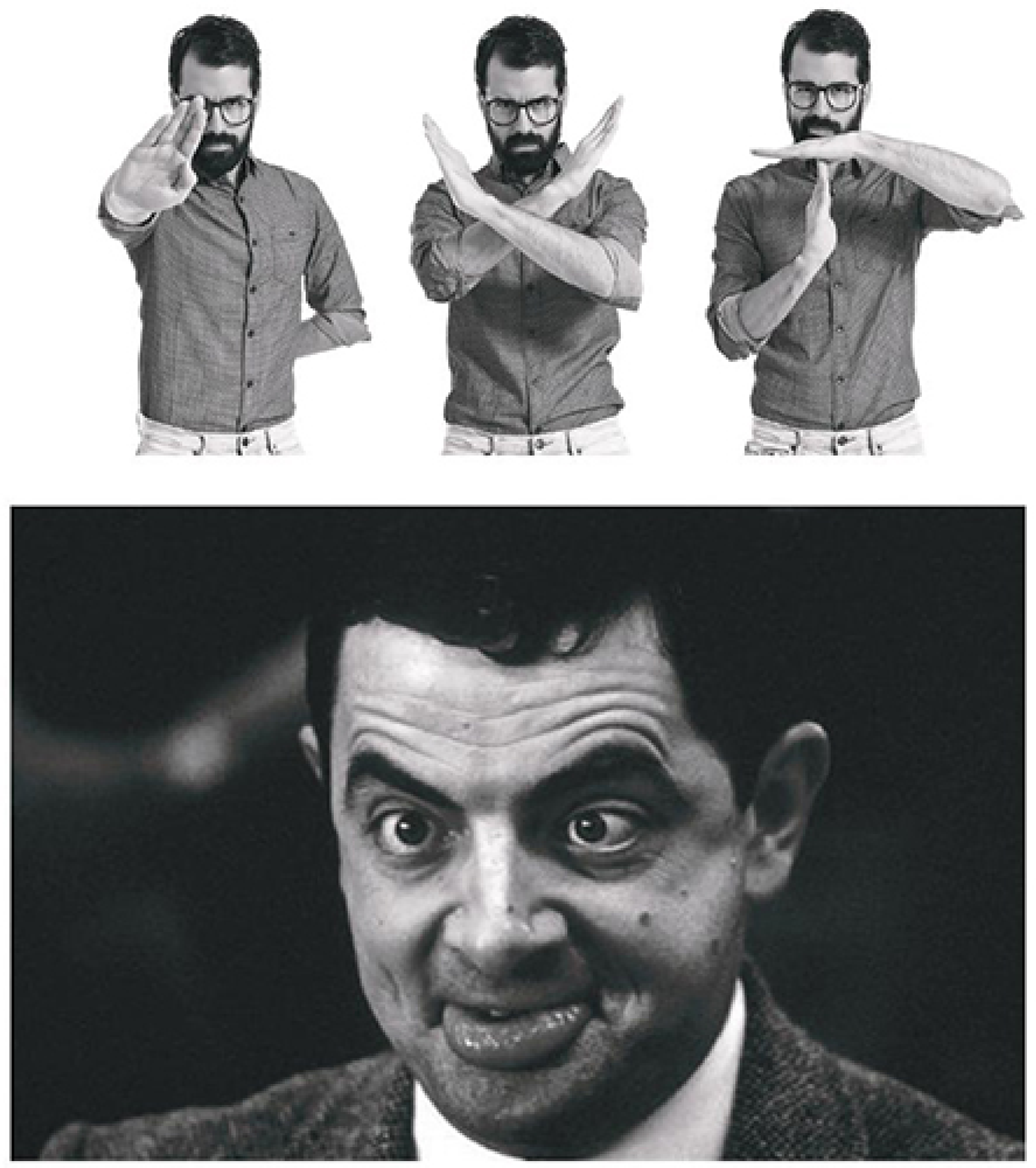

Fig. 3.5:
Un-intentional Expressions

3.2 Computer Supported Cooperative Work

Irene Grief and Paul M. Cashman coined the term Computer Supported Cooperative Work (CSCW) in 1984. CSCW addresses “how collaborative activities and their coordination can be supported using computer systems” (Carstensen and Schmidt)[4]. The term groupware is a synonym of CSCW. Ellis et al. define groupware as ‘computer-based systems that support groups of people engaged in a common task (goal) and that provide an interface to a shared environment’[6].

Classification of systems: Time/ Space Matrix

In 1988 Johansen classified the groupware systems using a matrix based on time of the activity (synchronous vs. asynchronous) and location of the collaborators (co-located collaboration vs. remote collaboration).

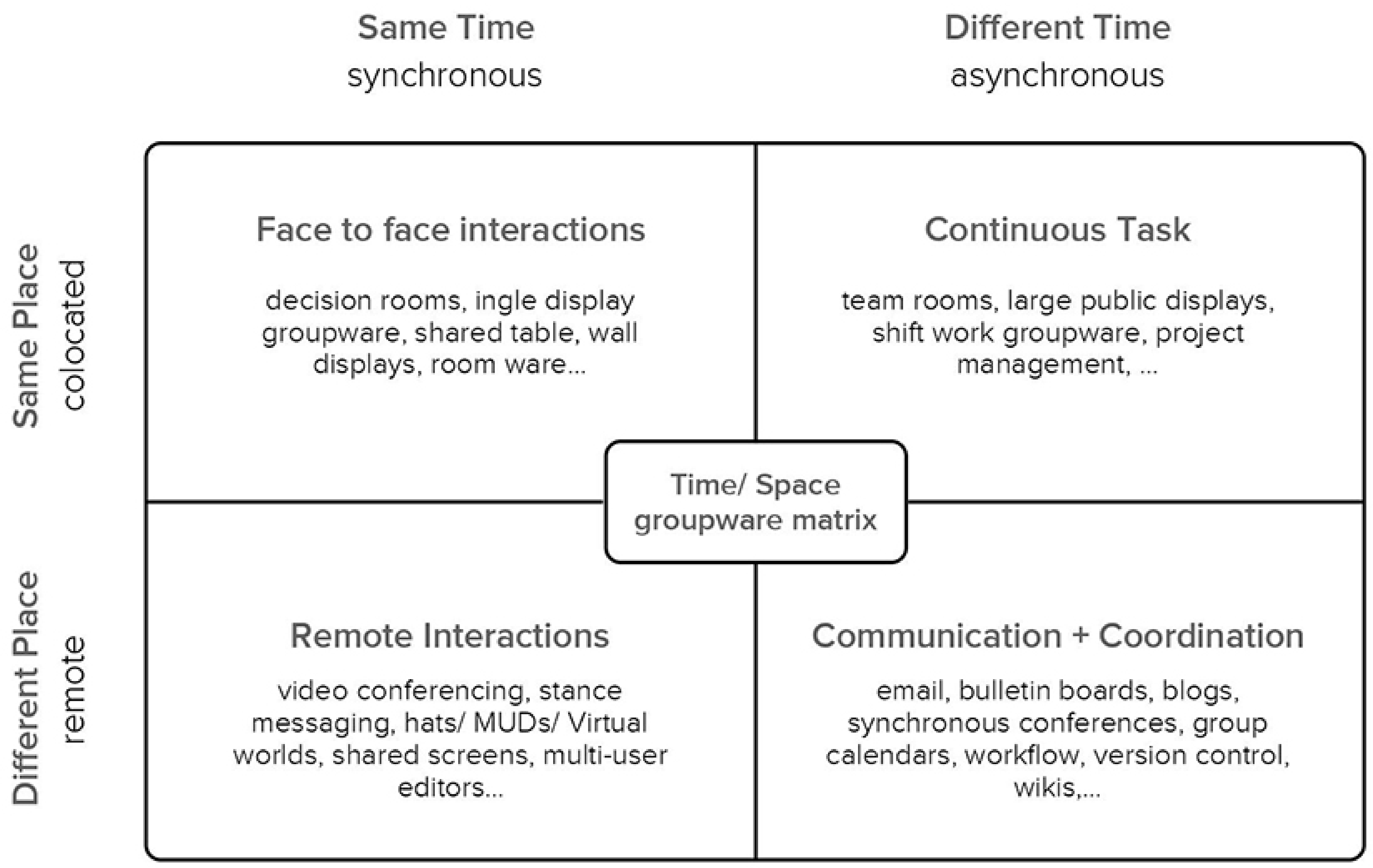

Fig. 3.6:
CSCW Time-Space Matrix, Johansen 1988

CSCW models and theories

A lot of theories, models, and framework have been proposed to design systems based on CSCW. These models are helpful to analyze the requirements for the operation and bring out the focus areas to develop an excellent collaborative platform.

1. Coordination Theory
Coordination theory is a set of principles that allows one to manage interdependencies between activities performed to achieve a goal.[7][13] It talks about various components of cooperation: Goals, Actors, Activities, Interdependencies. The theory focuses on coordination problems like identification of goals, mapping of goals to activities, ordering of activities, selection of actor for a different type of activities, allocation of resources for an activity, etc.

The theory does not consider the role of tools. The activity is a single task and is not divided into smaller tasks which make an activity.

2. Activity Theory
The theory defines activities as basic units of analysis. An activity is directly connected to an object which may or may not be tangible. The theory states that the change in state of an object proves the existence of an activity. It also breaks down a collaborative activity into actions and further into operations carried out by different participants[7].

An activity involves a community of participants. These participants within the community can be classified into active and inactive participants. Activity participants who are directly involved in an activity. Mediators mediate the relationships between different components. Tools mediate the relationship between the Active subject and material object. Rules mediate the relationship between active subject and other participants. Division of labor mediates the relationship between the object and the community.

3. Task Manager Model
This model develops around the concept of task. A task can be a project (result oriented),

a set of subtasks (procedure oriented), a folder which can be structured or unstructured containing all the information shared within a task [7,10].

A task makes use of resources like shared documents, shared services, communication and exchanging messages. There are multiple participants involved in a task with different levels of participation. Participants can be categorized into two major categories. Participants who have all the rights to use the resources and Observers who are more interested in the completion of the project or are there to monitor. There are no relationships defined between two or more tasks.

4. Object-Oriented Activity Support Model
OoActSM is developed around the concept of activity [7]. It defines activity as a structured object which contains sub-activities. Participants known as Actors execute these sub-activities. Execution of activity is done by a single actor or a group of actors. Each activity represents a context, elements created or manipulated by the activity, other participants involved in the activity and also the tools used or the manipulation of the elements. Each activity has a state, an execution history, and execution procedure.

5. Generic Conceptual Model
Farias et al. [7] proposed a generic CSCW model based on the above-explained model. The model consists of four crucial concepts, Actors, Activities, Tools, and Resources. An activity can be described as a Task, action or an operation. An Actor represents a subject, participant, observer, member or an interactant. Resources are objects, documents or information which are used while performing an activity. Tools facilitate the actor to perform a task or an activity.

According to this framework, an activity consists of Actions and sub-activities. Actions are short-lived whereas sub-activities can be further broken down.
The framework also looks into the relationships between different actors, roles an actor plays and policies which regulates relationships between different actors performing same kind of activity.

	Activity	Actor	Resource	Tool
Coordination theory	activity	actor	resource	-----
Activity theory	activity/ action/operation	participant, subject	object	tool
Task Manager	task/subtask	person, participant, observer	resource	-----
Action/Interaction theory	activity/action	member, interactant	-----	technology
OOActSM	activity/sub-activity	actor	document, information	tool

Fig. 3.7: *Terminology comparison between different CSCW models.*
Farias et al. (2000)

Koch et al. [9] classified collaborating systems into five parts based on social interactions

• **Co-existence**
Co-existence is allowing multiple users to share applications synchronously and provide users with information about the presence of others.
• **Communication**
Supporting explicit and implicit communication
• **Coordination**
Manage dependencies between activities, actors, and sub-goals
• **Consensus**
Offer support for the structuring of decisions, voting and evaluating, generating ideas and analyzing statements
• **Collaboration**
Real act of working together

These five classifications are the fundamentals of a CSCW system. A collaborative system should look into all these areas of concern.

Literature review equipped us to lay down the foundation of the platform. The study helped to organize the workflow of the project and also provided a direction to move further. The project is using mixed reality as the medium of collaboration. The following section talks about the technology and works in the field of CSCW using mixed reality.

3.3 Mixed Reality

In 1994 Milgram and Kishino[14,20] coined the term 'Mixed Reality.' Milgram proposed a Reality-Virtuality Continuum.

The Reality-Virtuality Continuum (RVC) is a scale with real and virtual environments on extreme ends. The real environment can be defined as our natural environment with no virtual element augmented. The virtual environment can be defined as a virtual world which is fully immersive without any real-world element present in the virtual world.
A VR experience presents us a virtual world by disconnecting us from the real world.

When we move from Real Environment towards virtual environment on the RVC scale, where we add virtual elements in the real world, it is known as Augmented Reality. Similarly when we move from virtual environment towards real environment on the RVC scale, where we add real world elements in the virtual environment, is known as Augmented Virtuality.

Augmented reality and augmented virtuality together are known as mixed reality. Mixed reality allows us to take advantage of AR and VR without disconnecting the user from the real world.

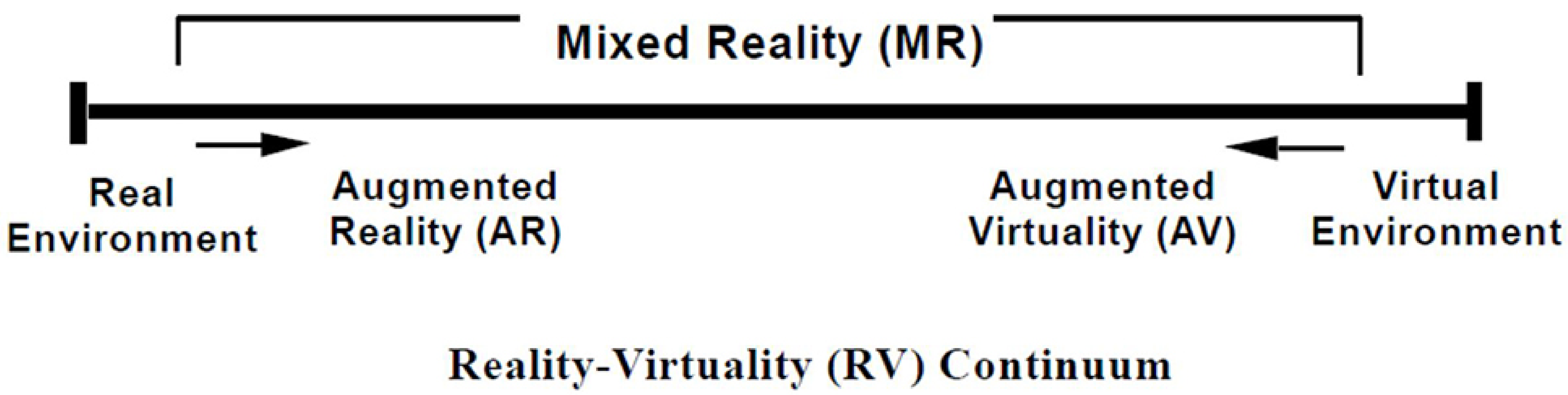

Fig. 3.8: *Reality-Virtuality (RV) Continuum*
Milgram and Kishino (2003)

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Augmented reality and augmented virtuality together are known as mixed reality. Mixed reality allows us to take advantage of AR and VR both without disconnecting the user from the real world.

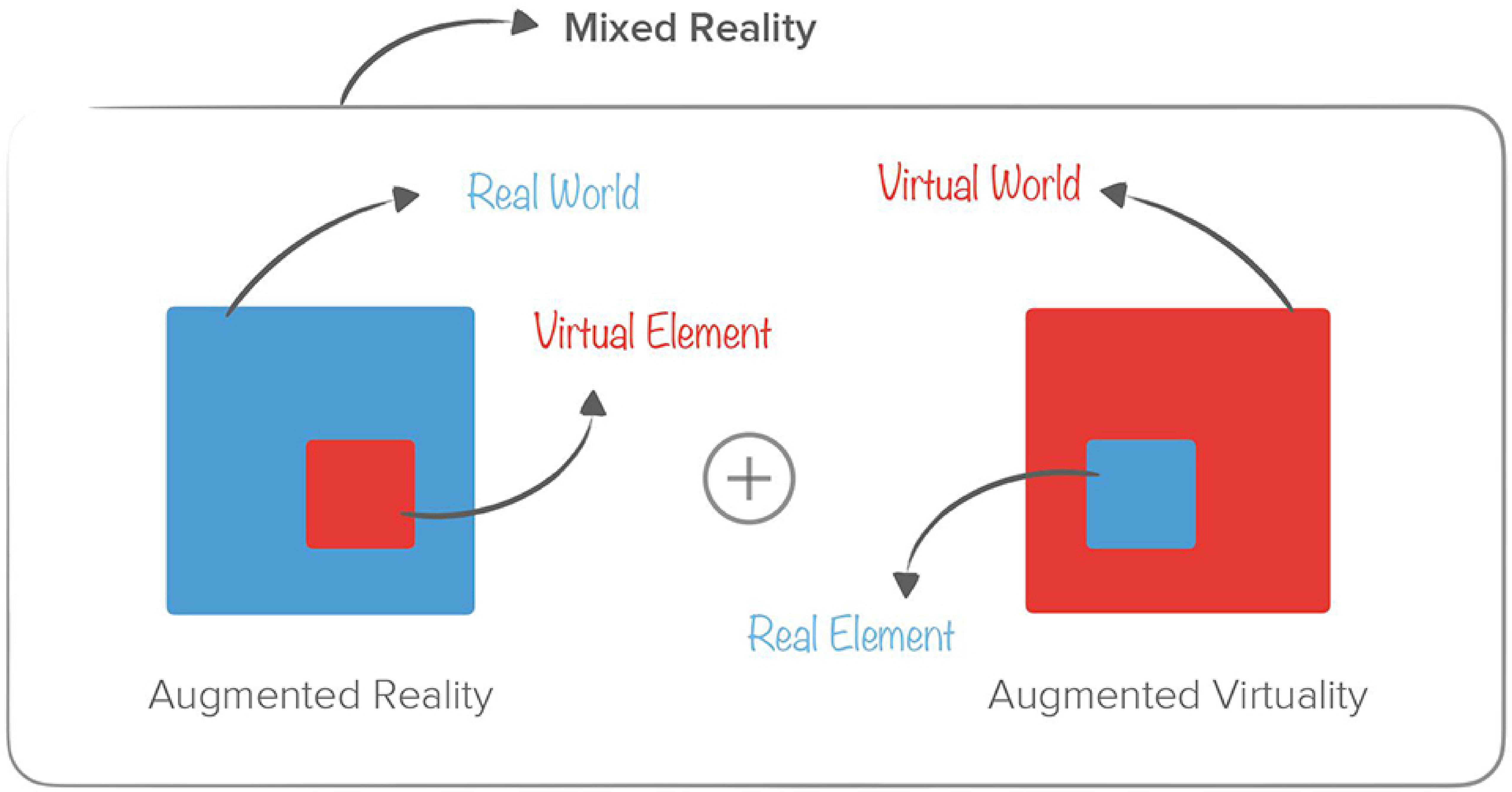


Fig. 3.9:
Representation of AR, AV and MR
Author

3.4 Collaborative Mixed Reality

The term collaborative mixed reality was introduced by Mark Billinghurst in 1999 [2]. Current CSCW interfaces often introduce seams and discontinuities into the collaborative workspace. A seam is a spatial, temporal or functional constraint that forces the user to shift among a variety of spaces or modes of operation [2].

The seam can be of two types

Functional Seams: Discontinuities between different functional workspaces, forcing the user to change modes of operation.

Cognitive Seams: Discontinuities between existing and new work practices, forcing the user to learn new ways of working.

Advantages of collaborative mixed reality

Schmalsteig et al. [19] identify five critical advantages of collaborative MR environments:

- **Virtuality:** Objects that don't exist in the real world can be viewed and examined.
- **Augmentation:** Virtual annotations can be augmented on real objects.
- **Cooperation:** Multiple users can see each other and cooperate in a natural way.
- **Independence:** Each user controls his independent viewpoint.
- **Individuality:** Displayed data can be different for each viewer.

Another significant advantage of using mixed reality is that the participants can use real-world elements/ objects while viewing virtual content.

M.Billinghurst et al.[1] experimented to measure the effectiveness of a 3D CSCW system. The experiment was conducted for local as well as remote collaboration. Five such scenarios based on the location of the participants were tested.
The five scenarios are as follows.

1. Real world - Real body (Shared Space)
2. Real world - Nobody (Remote Location)
3. Virtual World - No Body

4. Virtual world- Virtual Body
5. Virtual world - Virtual body - virtual walls

The result of the experiment showed that the users were able to perform better in the real world condition where they could see the other user (local collaboration). The results also showed no significant difference between the real world- real body and virtual world-virtual body without virtual walls scenario. Two confounding factors were also found from the experiment. Those were the use of body and non-body cues and the learning effect.

Looking into the previous work done in the field of collaborative MR applications, we found few models and frameworks which we discuss in detail in the following section.

Models/ frameworks related to Collaborative AR/MR

1. ASUR Model
(Dubios, Nigay & Troccaz, 2001) Proposed ASUR model for collaborative augmented reality [5]. Though the model was designed for a single user application but, few components are similar to that of collaborative systems. Similar to CSCW models ASUR has components like User(U) who interacts in the real world with an object of task (RTask), where R represents a real object. A tool is used for interaction with the object (RTool) provided by a computer system (S). The system (S) uses Input Adapters (Ain) and Output Adapters (Aout) for Augmenting the user's action or perception or both.

2. MBA (Model-Based Approach)
(Trevisan, Vanderdonckt & Macq, 2003) [5] proposed a set of models which cover all the requirements of an AR collaborative system.

Following models were proposed by them:

• User Model for representing the user roles and characteristics.
• Task model for representing the tasks that the user will perform with the application.

• Domain model for describing the data (real or virtual) that the application uses.
• Presentation model which represents the structure and content of the interface.
• Dialog model for describing the dynamic aspects of the model.
• Application model represents the hardware and devices used by the application.

3. IRVO model
IRVO (Interacting with real and virtual objects) is an interaction model designed for collaborative mixed reality systems [5]. The model represents the objects and tools used in an MR collaborative system and their relationships. The model presents three main categories of entities.

1. Users (U) - Collaborators/ Participants/ Actors
2. Domain Objects (O) - Resources/ Task Objects/

3. Tools (T) - Intermediate Objects (facilitate the user to perform task)
4. Internal Model (M) - Platform/ Application

Tool Object relationship: The model describes that the tools and objects can be Virtual as well as real

• Virtual Tool (Tv) • Real Tool (Tr)
• Virtual Object (Ov) • Real Object (Or)

Mixed object and tools which are partly real and partly virtual. Since in mixed reality we deal with real and virtual worlds at the same time, the transmission of the information from real to virtual world and vice verse is done using transducers. The R/V Boundary separates the real and virtual world. Boundaries also exist in the real world which separates different places within the real world.

Further, the model describes the user interactions using visuals, audio, and haptics. The information from the interaction travels from real to virtual world using Sensor and from virtual to real using effectors. Relationships are shown using lines which can represent actions, perceptions or communications.

4. Framework for collaborative AR applications
Tobias et al. proposed a taxonomy which divides collaborative AR systems into six dimensions and then further into different manifestations [3].
The taxonomy helps to define the essential characteristics of the collaborative application. It can also be perceived as an extension of CSCW matrix as it adds more dimensions including the space and time of the activity.

3.5 Collaboration in AEC Industry

Architectural projects involve a multidisciplinary collaboration. In architectural practice, the traditional way of collaborating is by exchange of 2D drawings. The data is exchanged or shared either electronically (email or cloud storage) or by sending physical sheets to the concerned stakeholders. [18]

As the building forms and structures are becoming more complex, 3D models are being used widely (digital or physical) for better comprehension when working with other teams. With the introduction and adoption of advanced CAD tools like BIM, the data is now being exchanged electronically in the form of digital 3D models with contains both geometric as well as non-geometric data.

3.6 Building Information Modeling

Building Information Modeling is service used in AEC (Architecture, Engineering & Construction) for collaborative working. BIM allows all the stakeholders to work on a single database and to be up to date with the changes and modifications made by different collaborators. The data is stored in the form of a 3D model which contains all geometric and no geometric data [18].

How does BIM work?
BIM uses a central server where a central 3D file is stored. Each collaborator creates a local file on their system which is linked to the central file on the server. Each collaborator has access to limited elements and can modify only those elements for, e.g., Architect has the authority to use architectural elements like walls, doors, windows, etc. whereas a structural engineer has authority to access beams, columns, structural slabs, etc. This is known as Model Element Authority. Each collaborator works on their part and syncs the local file with the central file on the server.

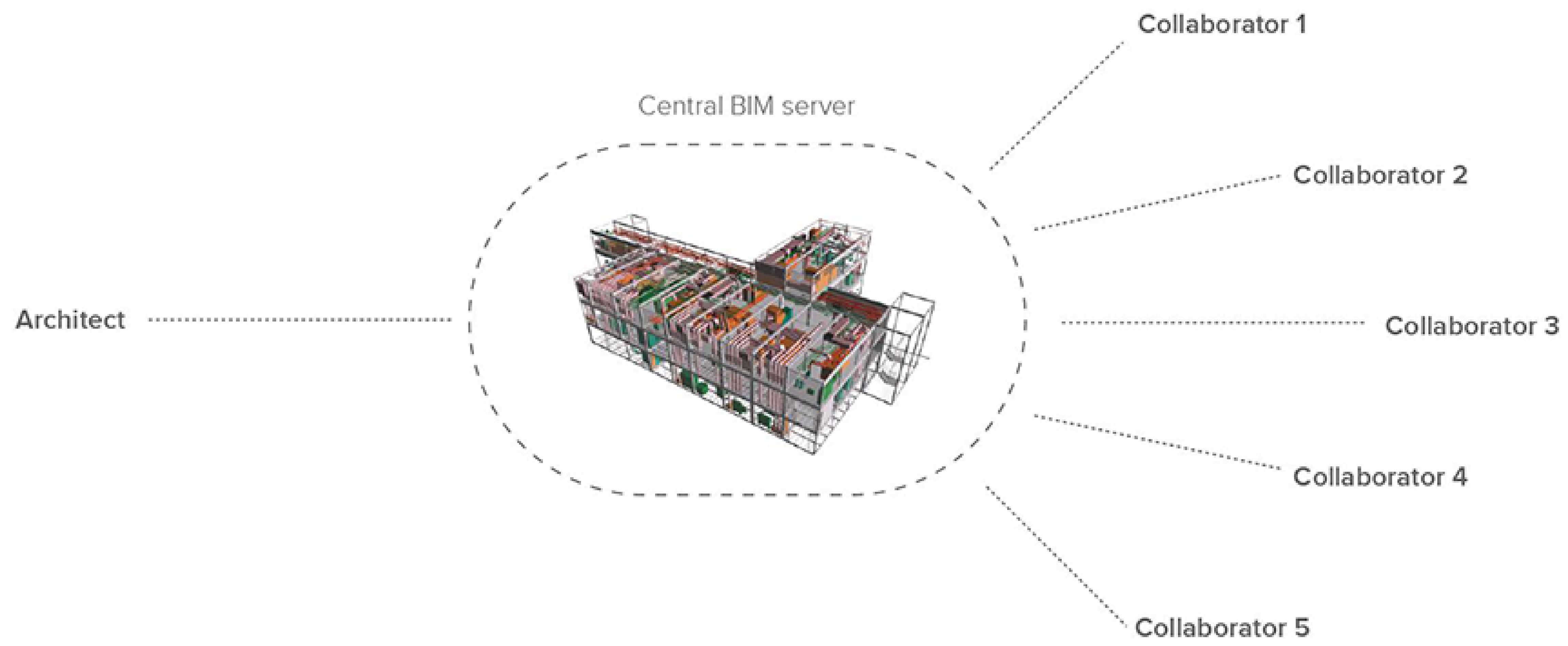


Fig. 3.10: *BIM (Building Information Modeling) central model and collaboration map*
Author

3.7 Related Works

There has been a lot of work done in the field of Architecture and AR. Majority of the work done is around utilizing AR for visualization purposes. Not much has been done in utilizing AR/MR for collaboration purposes.

Some of the notable work done in AEC context is ARTHUR project (Broll et al.). ARTHUR was a tabletop AR system for urban planning. The system made use of optical see-through Augmented reality displays with a decision support tool.

Duston and wang developed an AR system known as AR CAD for piping design. Th concluded with validated benefits which include enhanced space cognition and perception of piping design. Wand et al. developed MRCVE, which was aimed at supporting collaboration and spacial design comprehension in collaborative design. But all these projects were developed for co-located collaboration.

Some work on applying AR to BIM is also there. Ning Gu et al. describe an Interface connecting AR and BIM server. Another work by Wang et al. where they created a mobile-based application to visualize BIM data in augmented reality. Currently, Trimble is also working on seamless switching from a desktop environment to MR environment to visualize 3d models.

4 Primary Study

This section includes the data collected through Semi-structured interviews with the stakeholders and knowledge from self-experience.

4.1 Stakeholders

The number of stakeholder increase or decrease depending on the scale and type of a project. For this study, we have considered a small-medium scale project. The collaborators taken for the study are present in all project regardless of scale. Following are the principal collaborators in an architectural project:

1. Architect
2. Structural Engineer
3. Electrical Consultant
4. Plumbing Consultant
5. HVAC Consultant
6. Contractor

4.2 User Interviews

Semi-structured interviews were conducted with stakeholders from all disciplines which consisted of 11 Architects, four structural engineers, 5 MEP (Mechanical, Electrical & Plumbing) consultants. The interviewees were chosen based on different industry experience levels, type of projects, the scale of projects, adaptation to newer systems and office sizes.
The interviews were aimed to analyze the following.

• Collaborative practices in the office
• Resources used while collaborating
• Collaboration tools used
• Communication methods (Local or remote)
• Information Exchange methods
• Hindrances in collaboration
• Shared resources

Major insights from user interviews

1. Communication by email, WhatsApp, Voice Call, Video conferencing
2. Sharing of visual (photos and video) to help remote collaborator visualize the situation.
3. 3D models are advantageous to understand complex designs and details.
4. Wrong perception of the scale of space from viewing 3D on the screen.
5. 3D model is created in the concept stage and keeps on refining.
6. Simulations are necessary to understand the output.
7. Lack of communication when working on BIM.
8. Collaborators are unable to comprehend the 2D details.

4.3 Stages of an architectural project

Architectural projects can be dissected into various stages. The following stages are based on the semi-structured interviews done with the stakeholders.

1. Client Requirements
2. Concept Evaluation
3. Approval Drawings
4. Development
5. Construction
6. Handover

The figure tries to demonstrate a general time-line of a project. Different collaborators join the project at different stages.

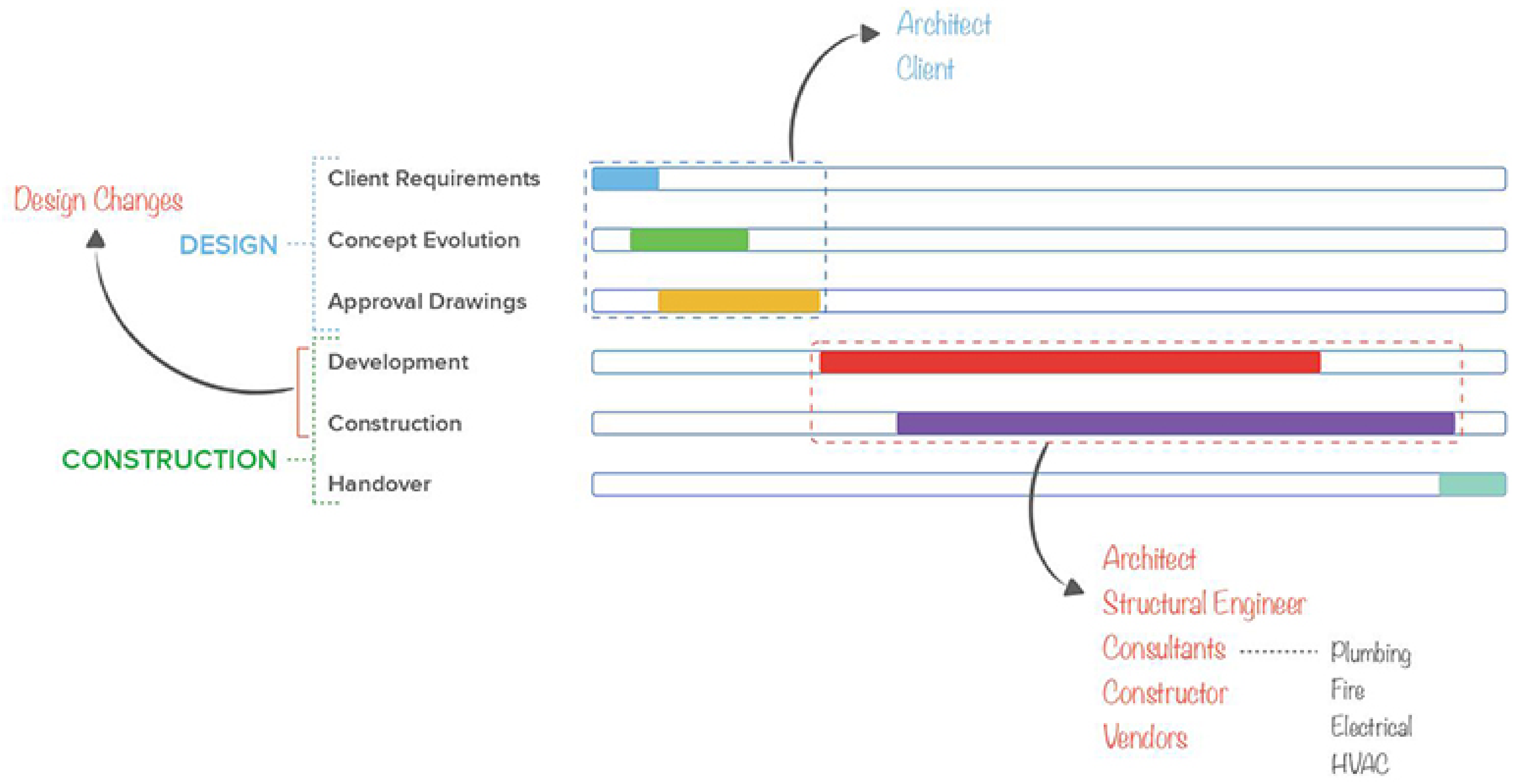


Fig. 4.1: *Tentative time-line of AEC project*

Author

The stages can be grouped into two majors chunks, design and construction. The maximum collaboration happens during the construction stage, especially a lot of design changes happen during the development and construction time.

4.4 Shared resources

Resources are the objects which are generated or manipulated during the collaborative activity. These resources are fully or partially accessible to all the stakeholders.
Resources can be Real objects as well as virtual objects.
Following are the resources used by the collaborators during an architectural project.

1. 3D model of the building and site

A 3D model of the site and the building is created at the concept stage of the project and is then modified until the end of the project. A BIM model is highly detailed in comparison to general 3D models. It comprises different layers which contain different elements. These different layers come from different disciplines working together on a project. These are Architecture, Structure, and System. System part consists of MEP (Mechanical, Electrical, and plumbing) layers.

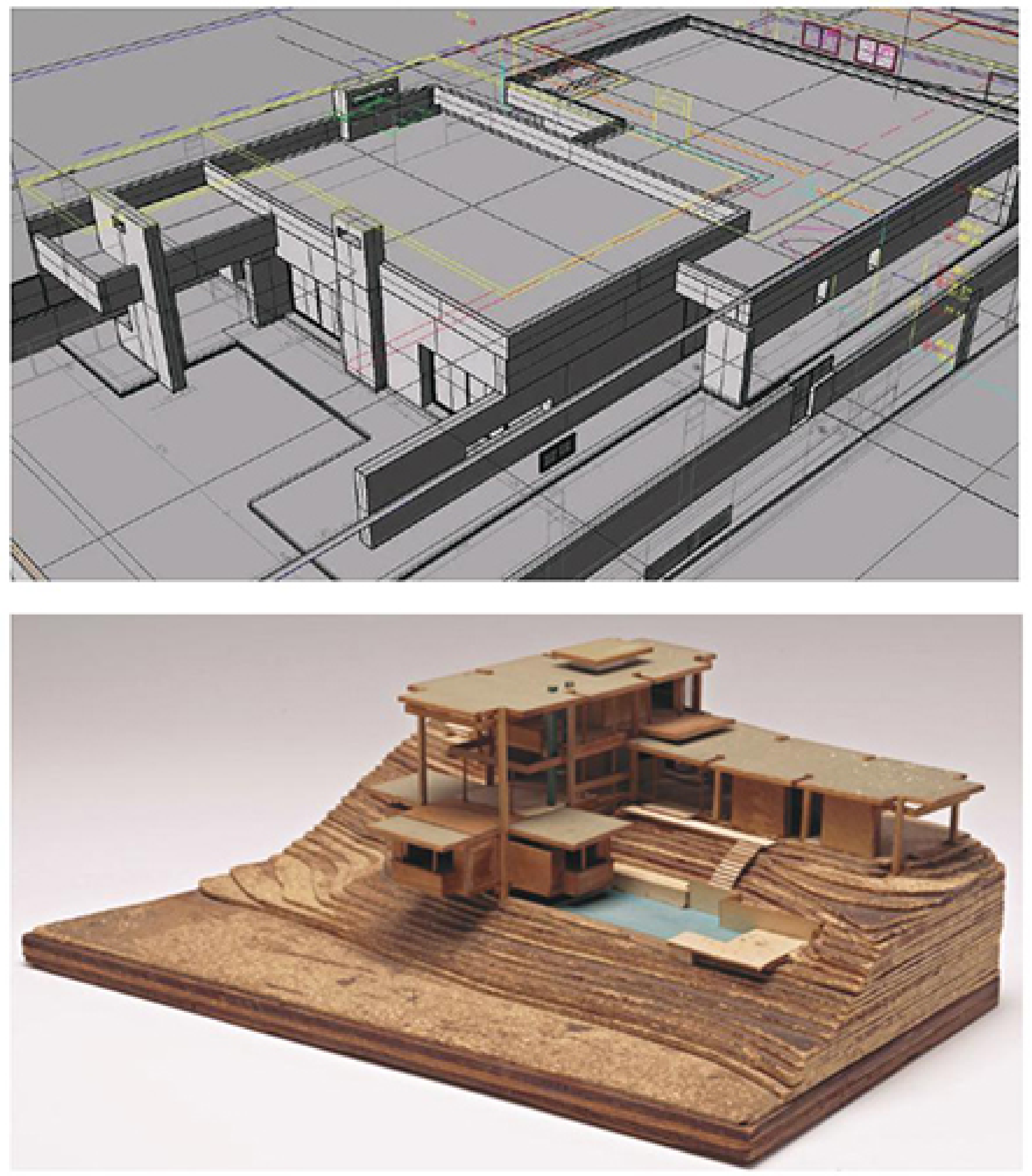


Fig. 4.2: *Digital 3D model (Top)*

Physical model (Bottom)

Each layer has numerous elements, or group of elements for, e.g., Architectural Layer would consist of walls, roof, windows, doors, etc.

A BIM model consists of non-geometric data as well. Non-geometric data is referred to the properties of the elements.

2. 2D drawings

The collaborators generate different kinds of drawings during the project. The types of drawing sheets are:

- Plans
- Sections
- Elevations
- Details

3. Actual Site

After the commencement of construction on the physical site, all the collaborators visit the construction site regularly for review meetings and to get work updates. Construction issues generally demand site visits.

4. Videos/ Images

Videos and images of different interests are shared among the collaborators. For e.g. sketches, pictures from construction site, material photos, etc.

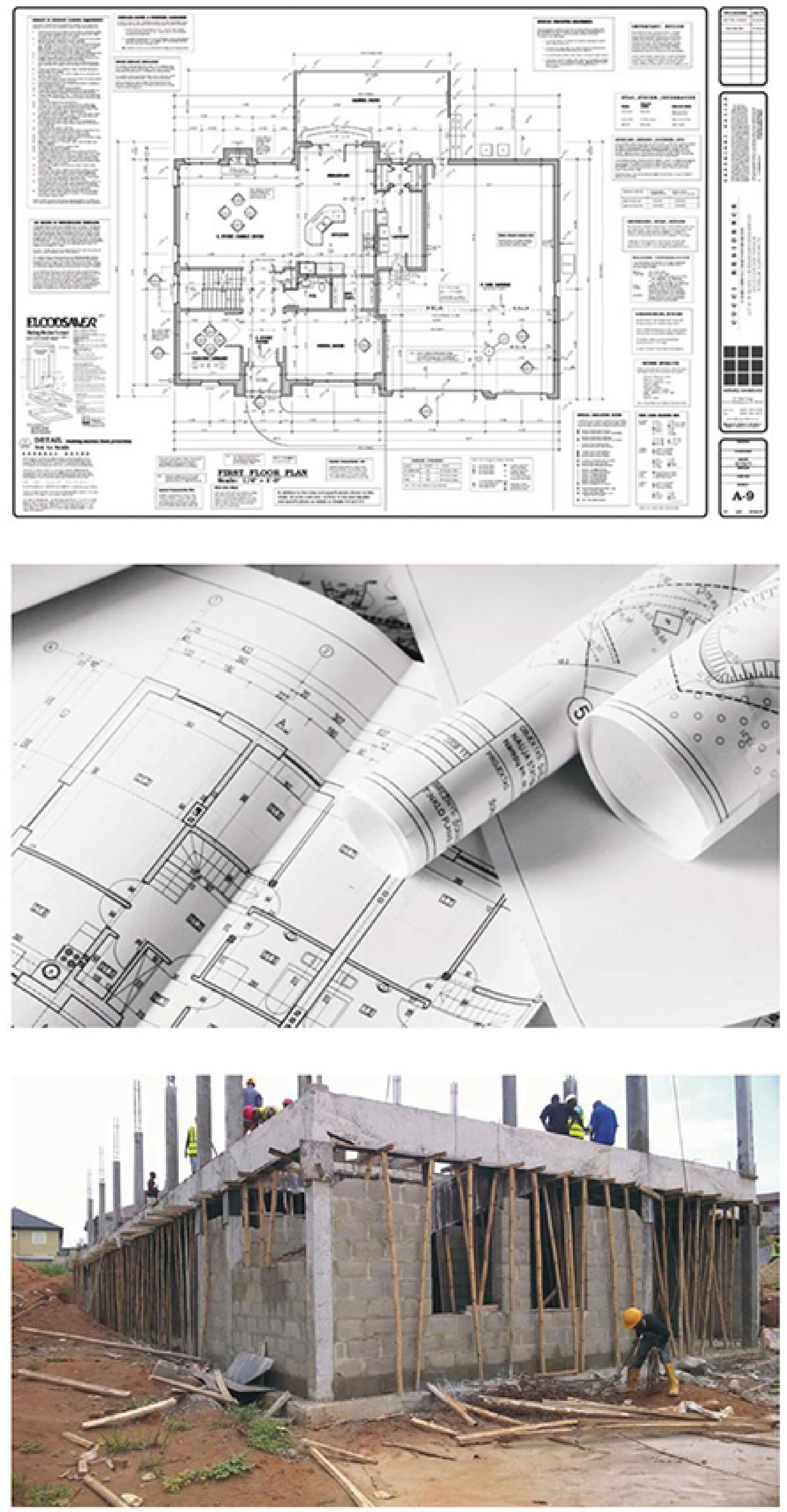
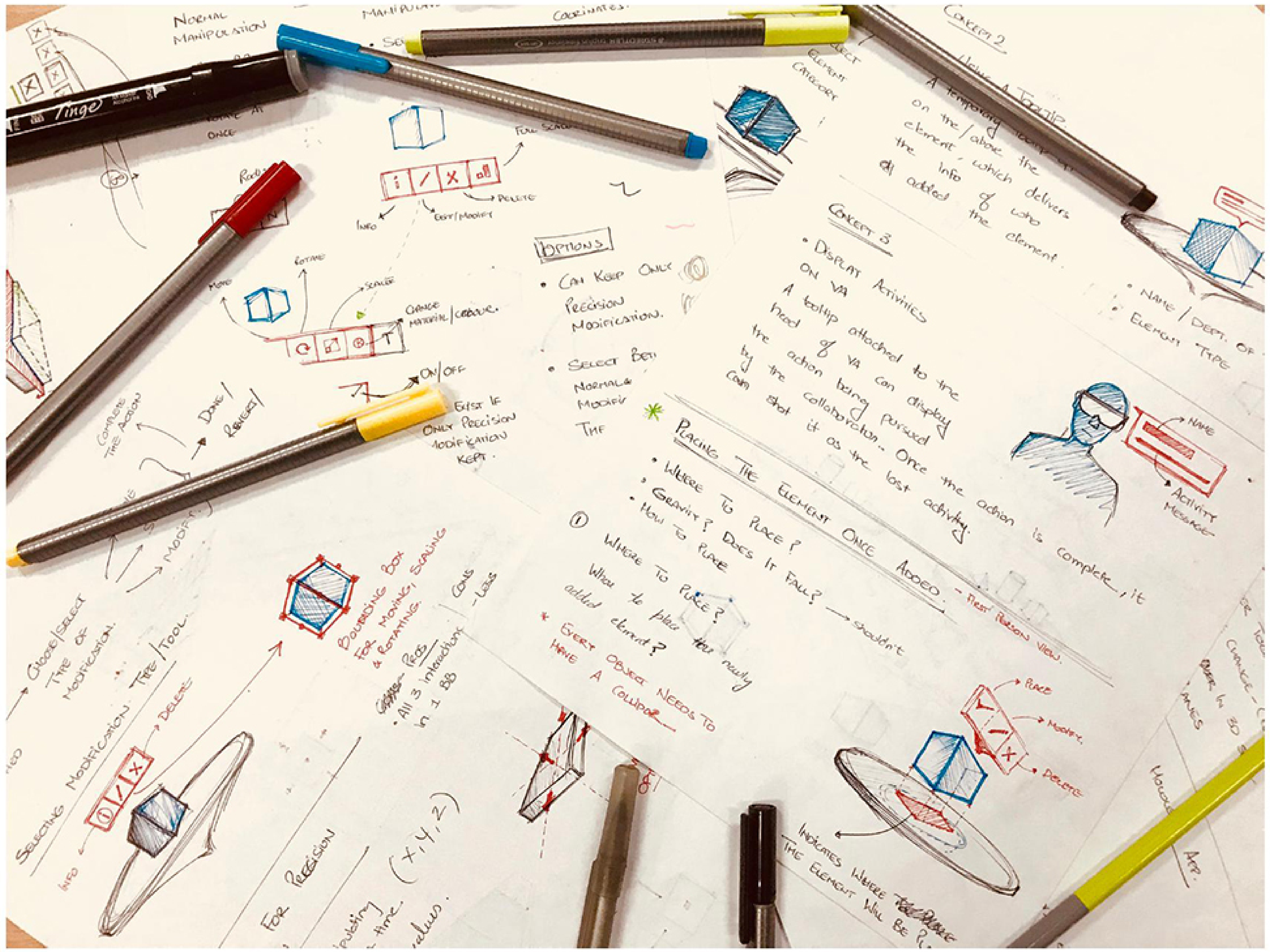


Fig. 4.3: *Construction drawings(img.1&2)*
Construction site (img. 3)

5 Design



5.1 Scenario Identification

We identified four scenarios based on the time-space matrix (Ref.). The identified scenarios represent only synchronous activities, both in the same space (Local Collab.) and geographically dispersed locations(Remote Collab.). Office space and the actual site of construction are taken into consideration while describing the scenarios.

Local Collaboration Scenario 1

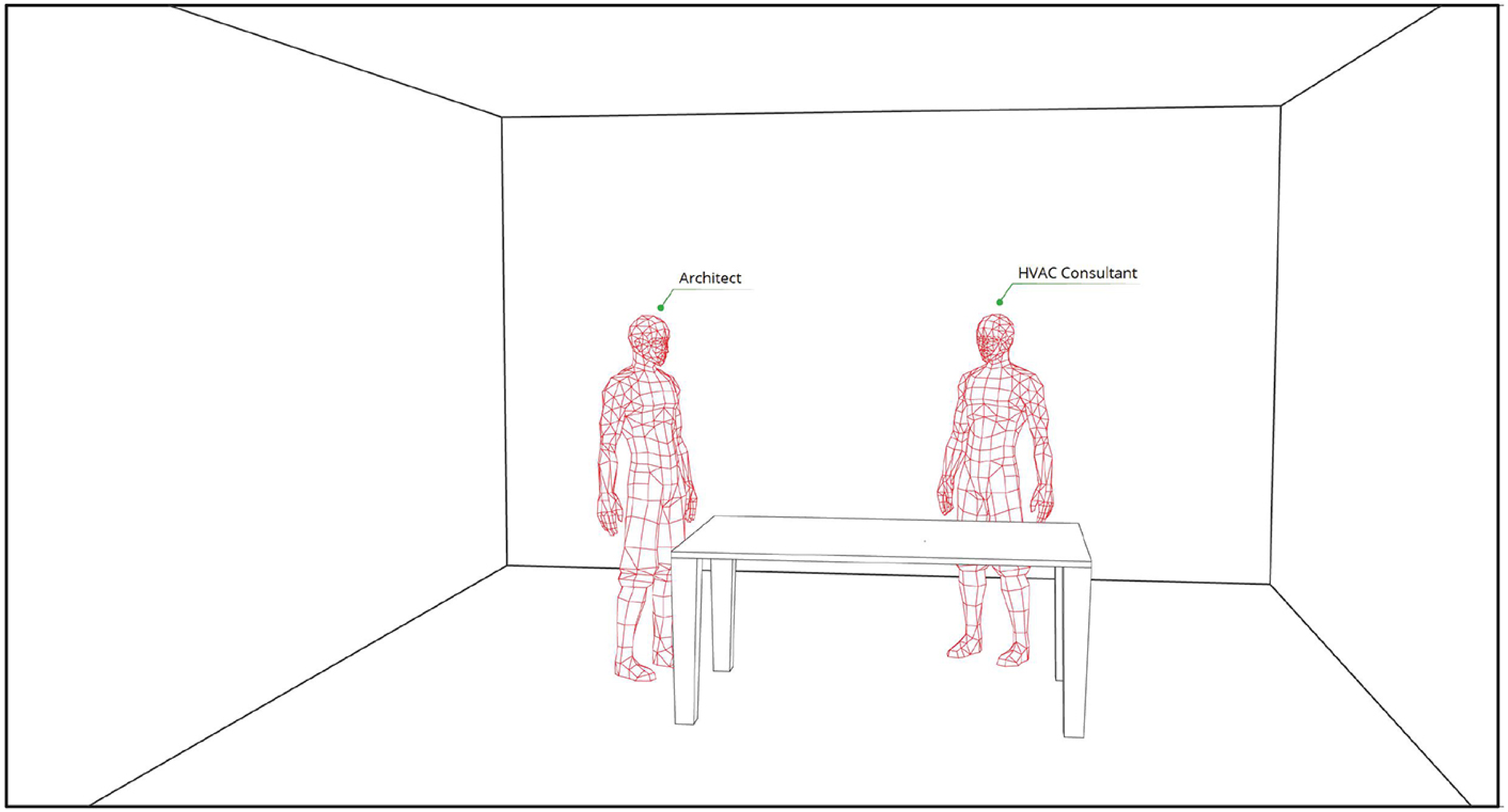


Fig. 5.1: *Office space: Co-located collaboration, Author*

Scenario 1

Fig. 5.1 presents a scene where two members from different disciplines (an architect and an HVAC consultant) are present in the same space. The members can see and hear each other. The location in the given scenario refers to an office space.

Local Collaboration Scenario 2

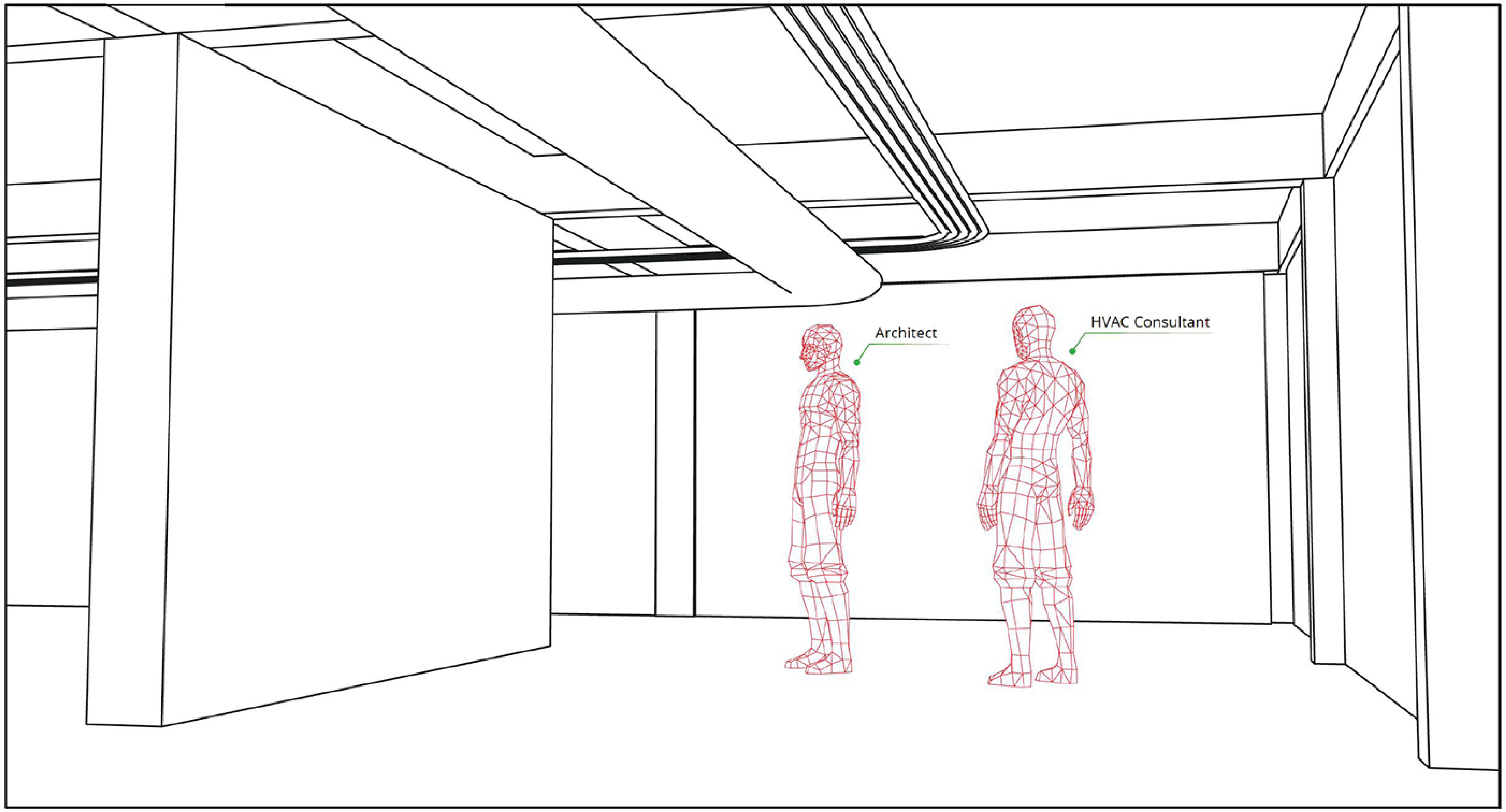


Fig. 5.2: *Construction site;Co-located Collaboration, Author*

Scenario 2

Multiple site inspections are set up during the construction phase of the project. Collaborators from different disciplines travel to the actual site of construction for site inspections and for meeting other collaborators. The Fig. 5.2 portrays a scenario where the architect and the HVAC consultant are present on the actual site of construction.

Remote Collaboration Scenario 1A

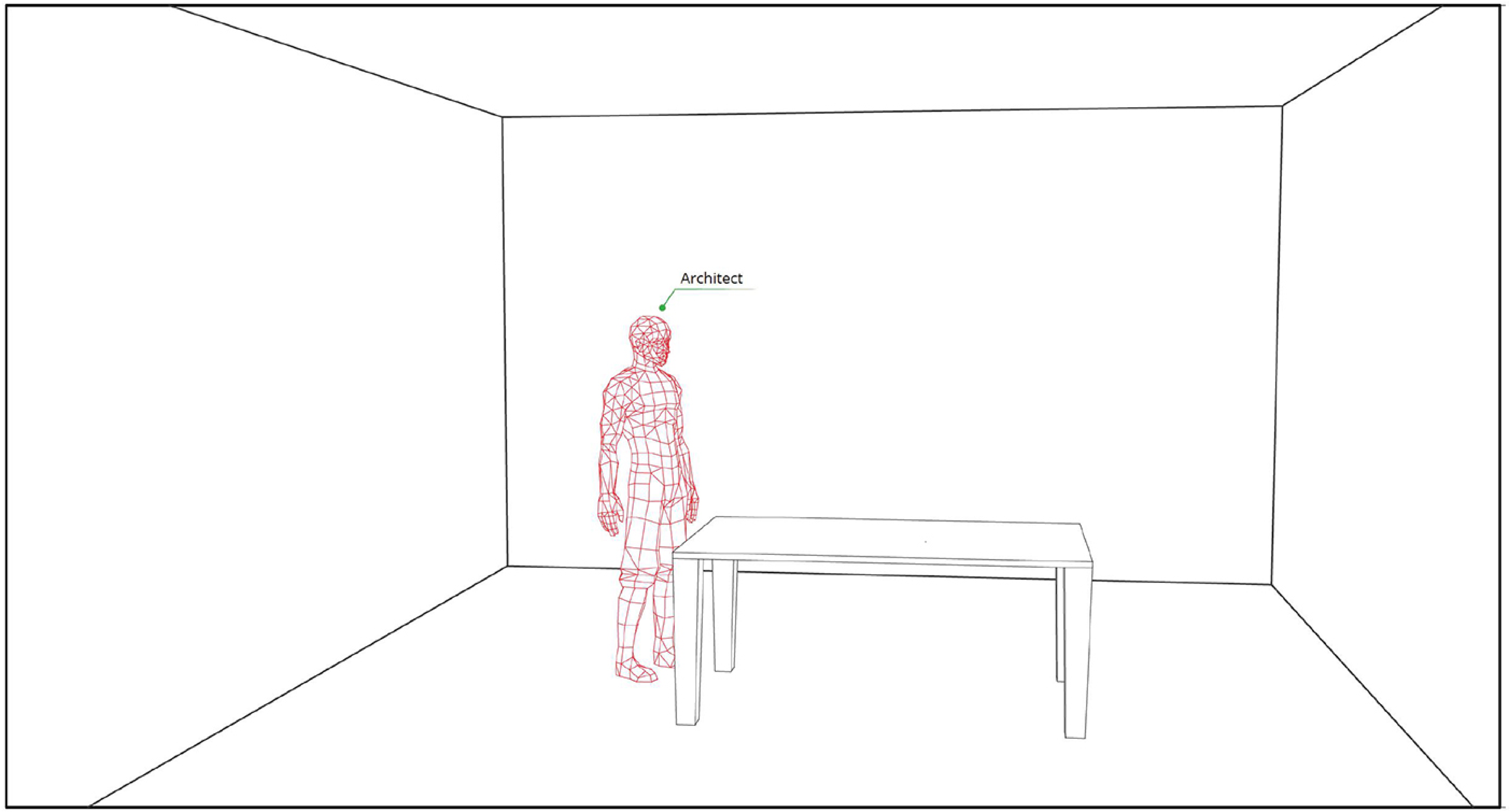


Fig. 5.3: *Office Space (Architect) Remote Collaboration, Author*

Scenario 1A, 1B

Many times the collaborators are geographically dispersed, due to which traveling becomes a necessity for conducting meetings in a shared space. The fig. 5.3 & 5.4 portray a scenario where the collaborators (architect and the HVAC consultant) are present at geographically dispersed locations .i.e. their respective office spaces.

Remote Collaboration Scenario 1B

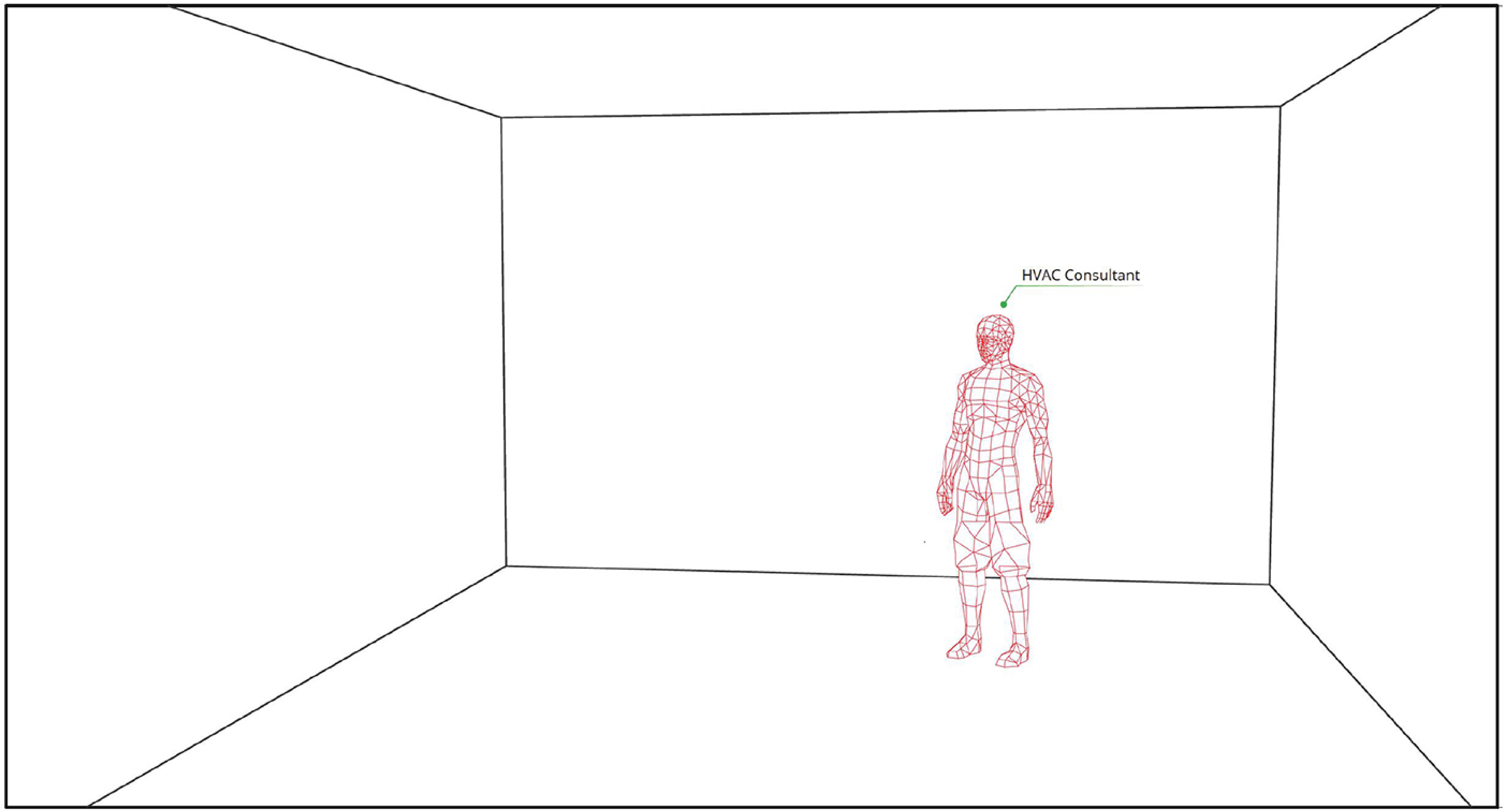


Fig. 5.4: *Office Space (HVAC) Remote Collaboration, Author*

Remote Collaboration Scenario 2A

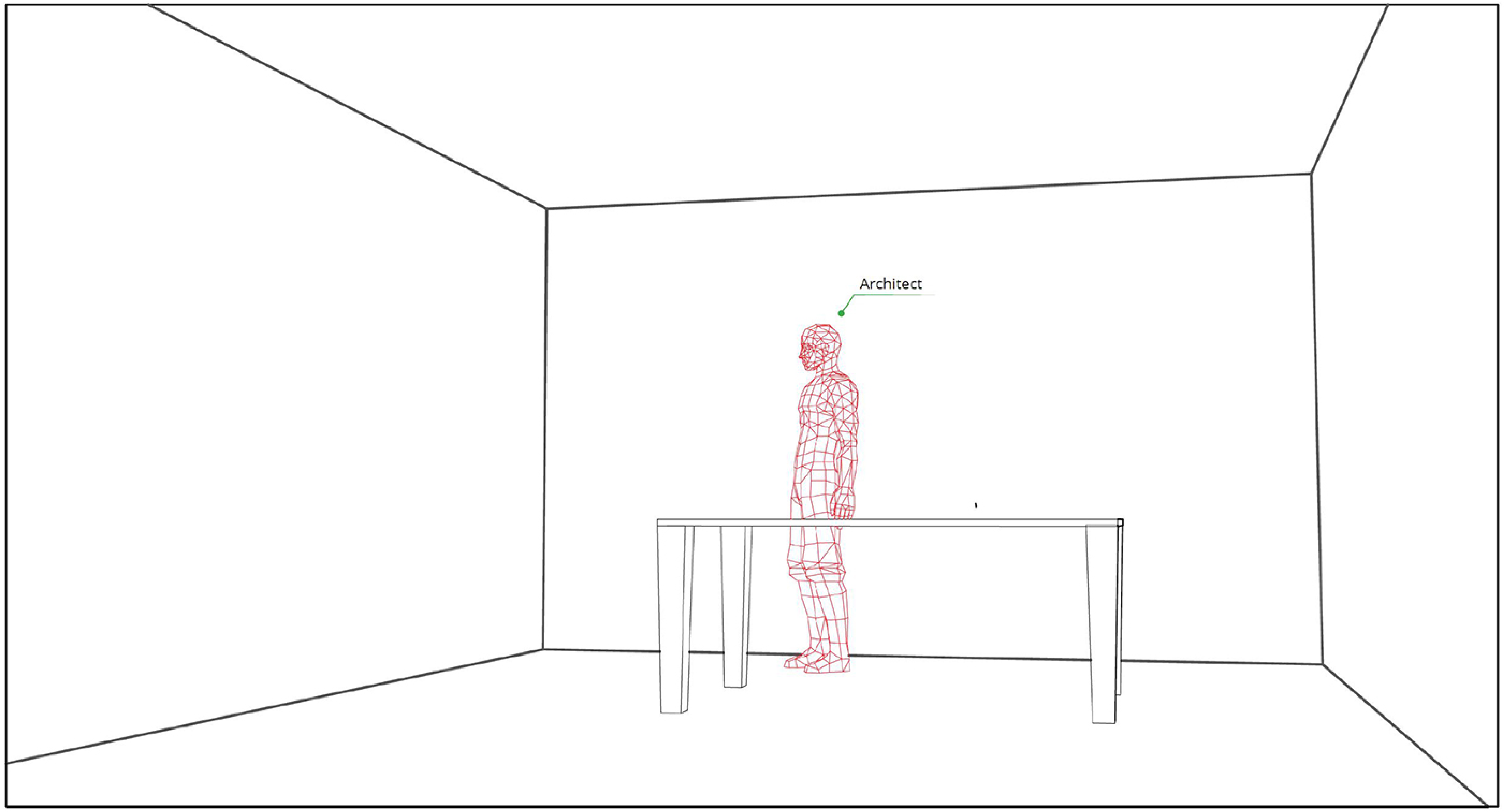


Fig. 5.5: *Office Space (Architect) Remote Collaboration, Author*

Scenario 2A,2B

Site inspections or the meetings held on the actual site of construction demand traveling to the location at a specific time which might not be feasible for everyone. The fig. 5.5 & 5.6 portray a scenario where the architect is present in his office space, whereas the HVAC consultant is at the actual site of construction.

Remote Collaboration Scenario 2B

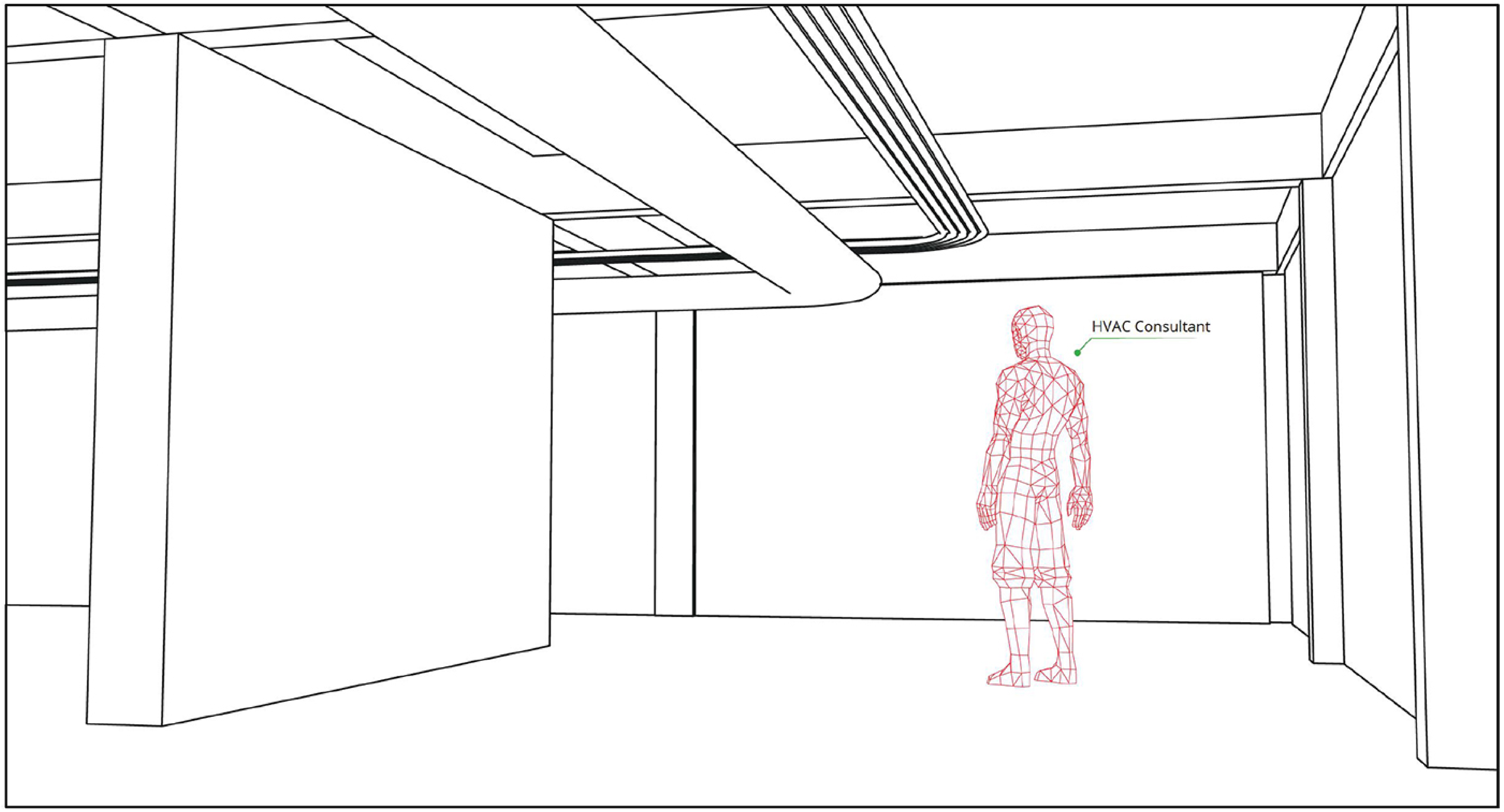


Fig. 5.6: *Construction Site (HVAC) Remote Collaboration, Author*

5.2 Concepts of CSCW

As per the models studied and compared by Farias et al. [7] there are four essential concepts in CSCW which are actors, activities, resources, and tools.
Collaboration happens when an actor performs an activity by using a tool which results in change, in a state of a resource.

We define these components as per our context. All the collaborators in an AEC project like architects, structural engineers, MEP consultants, etc. are the actors who perform collaborative activities. Resources include the data sets shared among all the collaborators, which can be in the form of 2D drawings, digital 3D models, photos, videos, etc. Tools would be a set of interactions which will allow the user to perform specific activities for manipulating the resources.

5.3 Scenario Design using Mixed Reality

Since we have defined the components of CSCW in our context, we introduce a mixed reality based system in the above-identified scenarios. The aim is to determine the practices of using the mixed reality groupware system in the identified situations enabling users to execute collaborative activities.

Local Collaboration Scenario 1 (Designed)

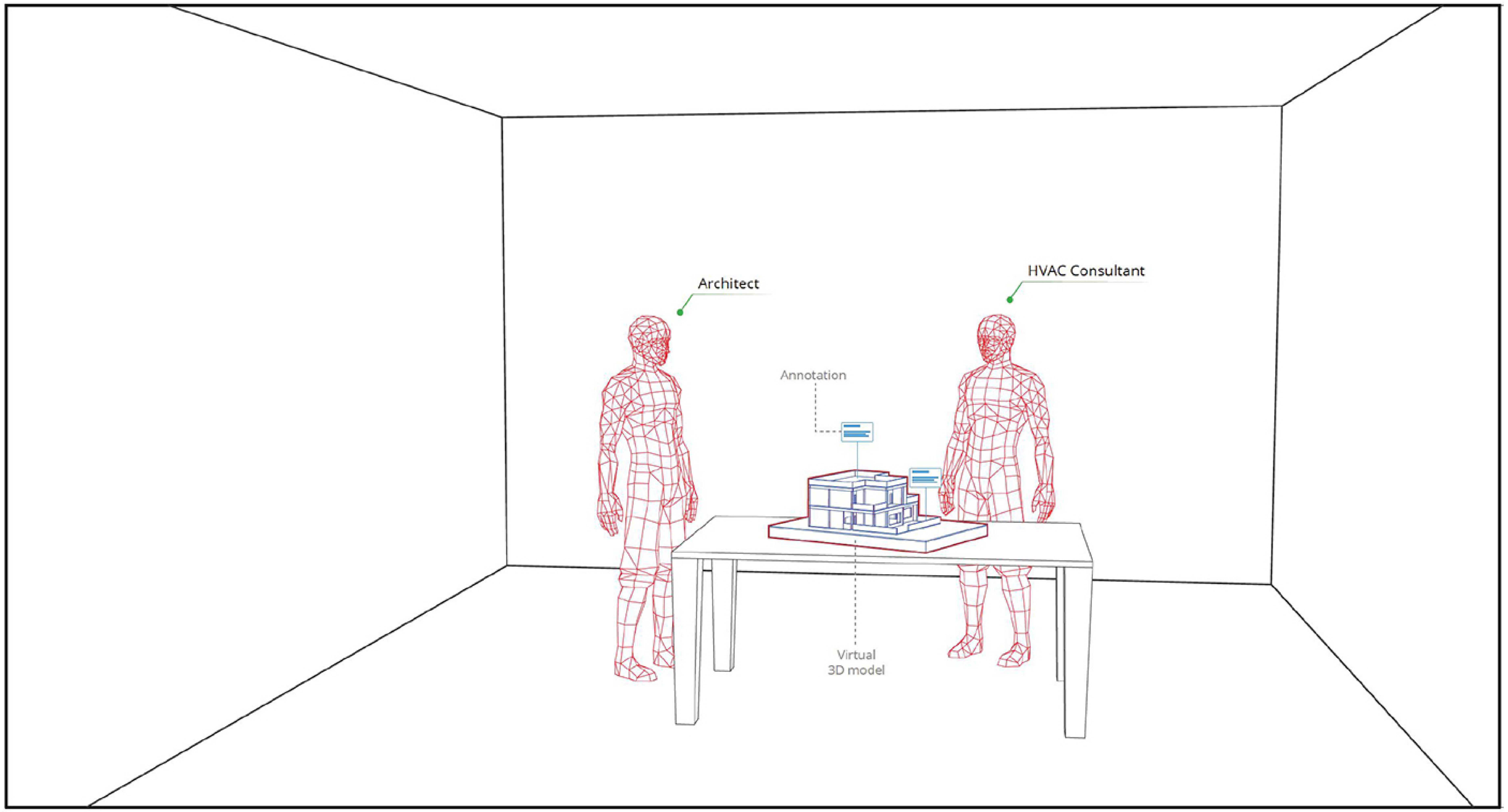


Fig. 5.7: *Office space: Co-located collaboration, Author*

Scenario 1
In Fig. 5.7 both the users are present in a co-located space where they can see and hear each other. The participants can view a shared virtual model of the building and collaborate locally.

Local Collaboration Scenario 2 (Designed)

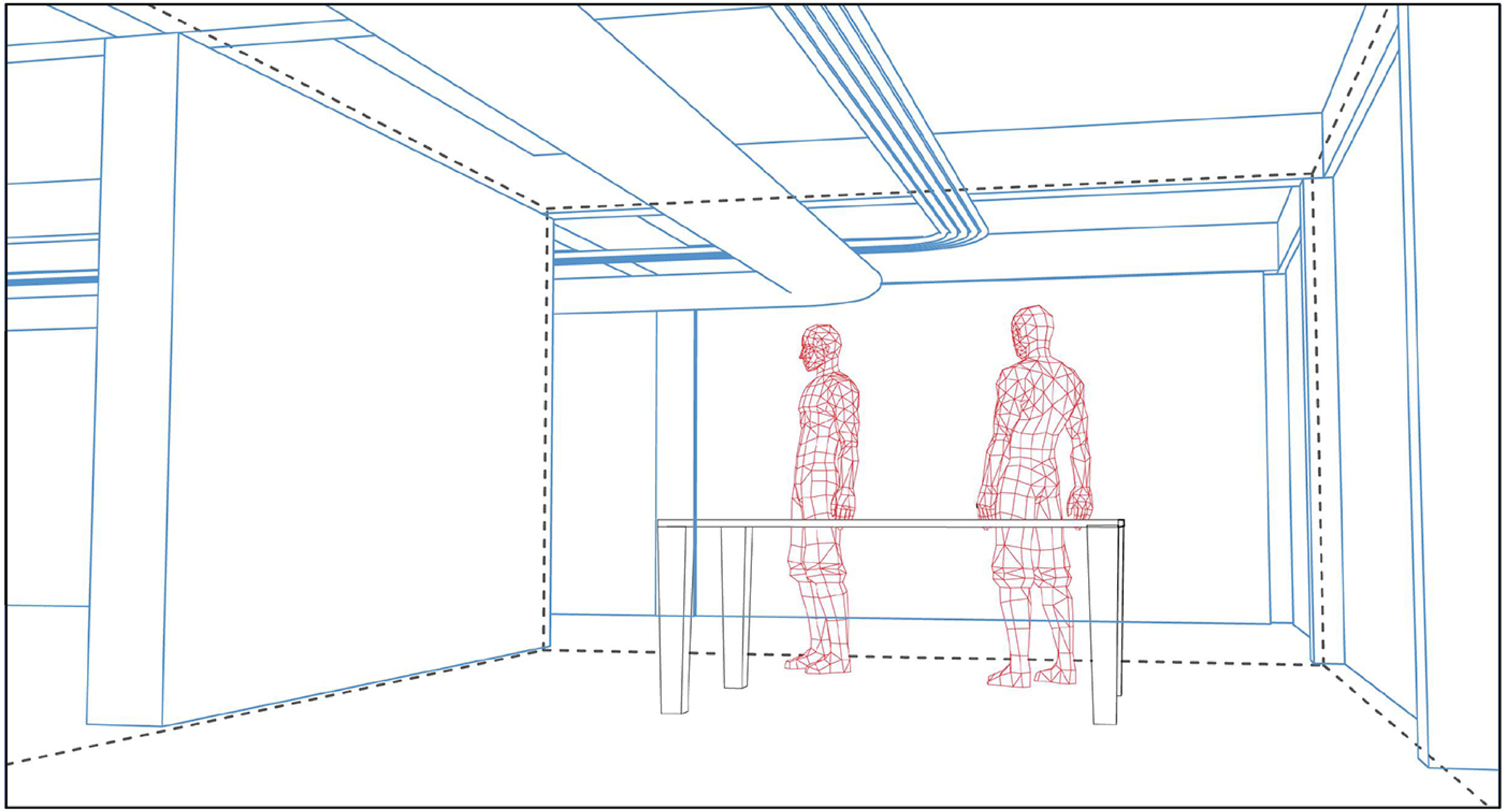


Fig. 5.8: *Office space: Co-located collaboration, Author*

Scenario 2

Fig. 5.8 shows another possibility based on augmented virtuality, where the model can switch from a scaled version as shown in Fig 123 (b) to a 1:1 scale version. The users are now inside the virtual model of the building and perceive elements at actual scale.

Local Collaboration Scenario 3 (Designed)

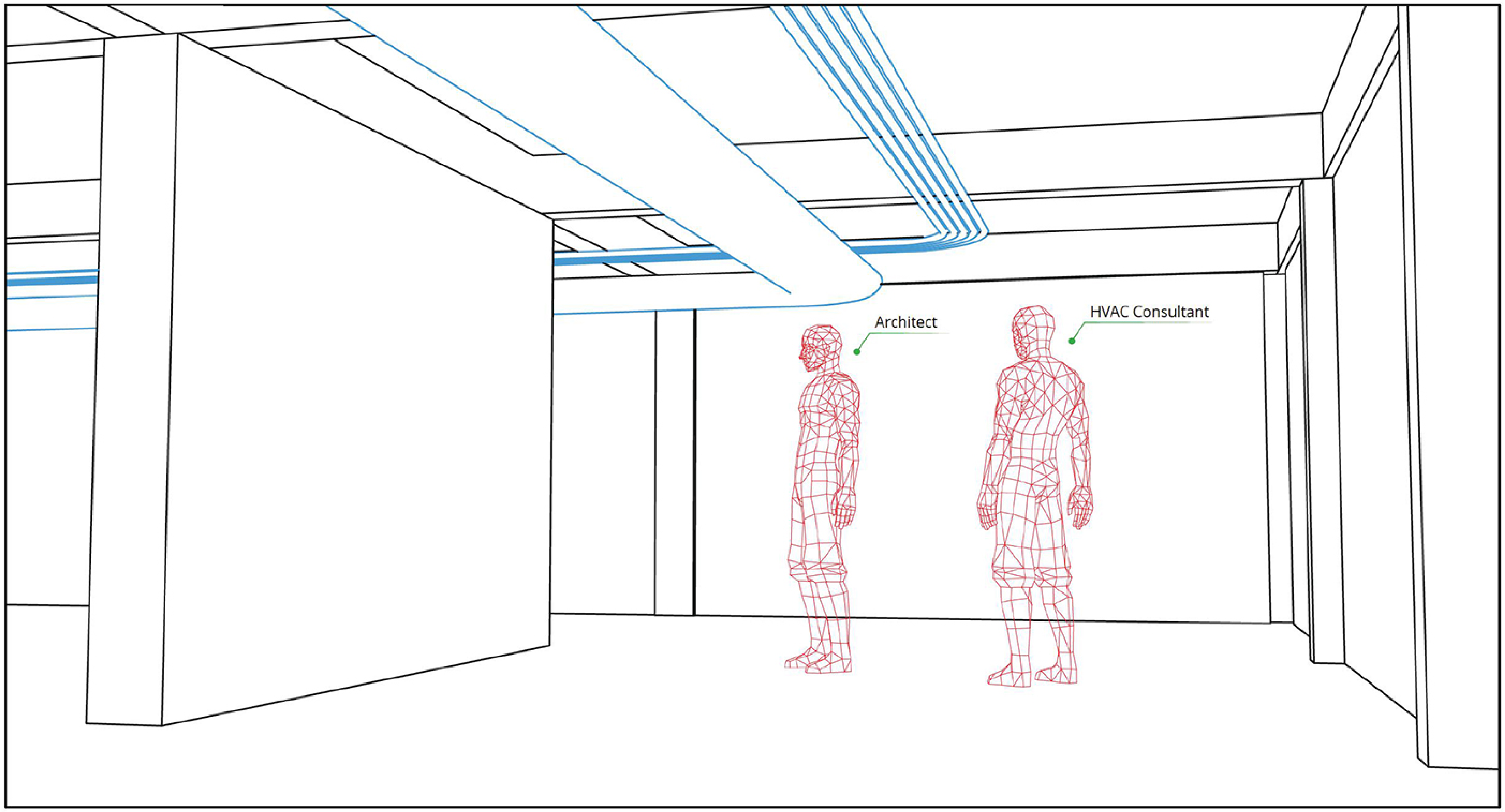


Fig. 5.9: *Construction site;Co-located Collaboration, Author*

Scenario 3

Fig. 5.9 represents a scene where the collaborators are present at the actual site of construction. The users can perceive shared virtual elements in the context of the construction site in 1:1 scale.

Remote Collaboration Scenario 1A

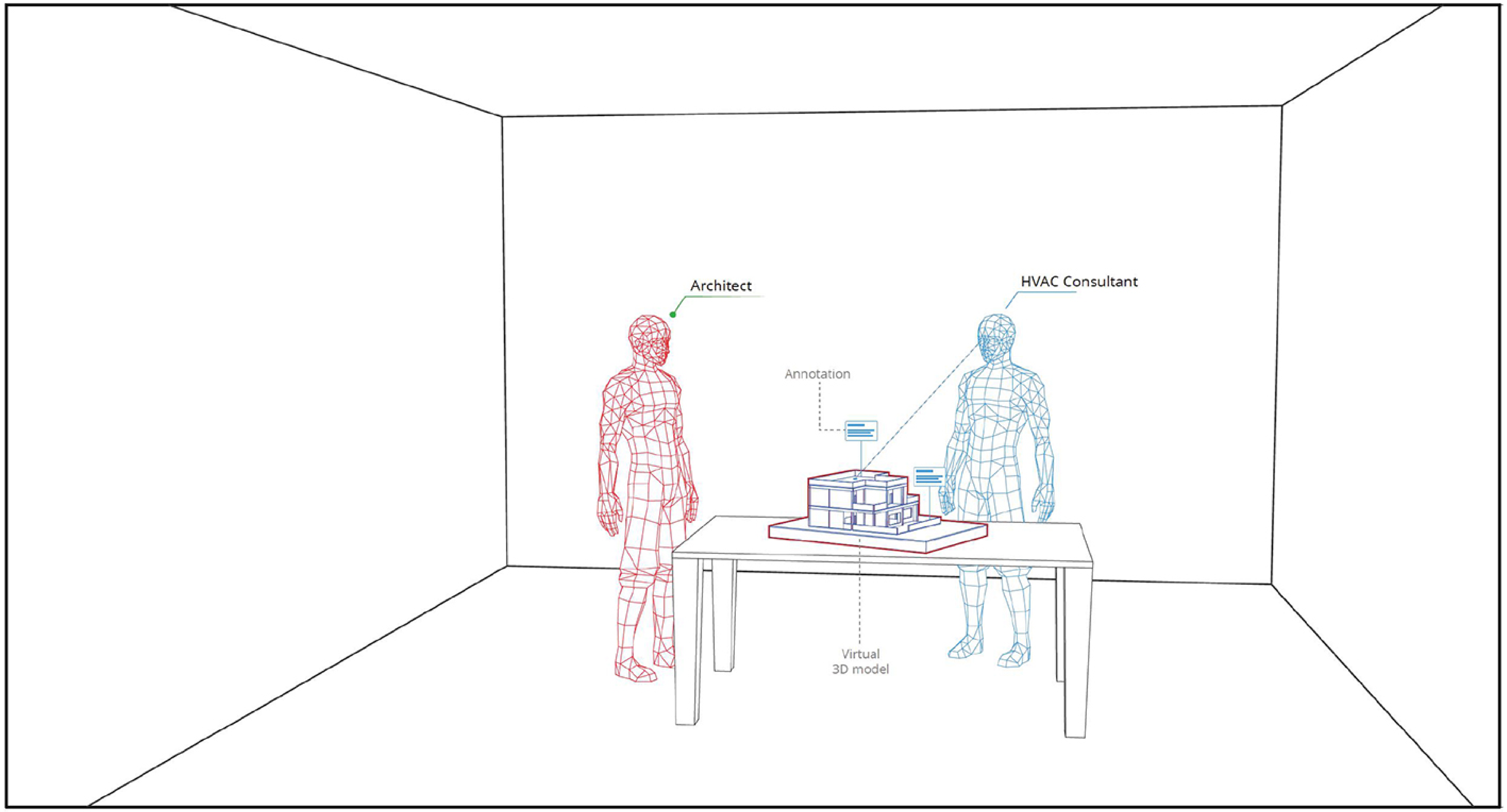


Fig. 5.10: *Office Space (Architect) Remote Collaboration, Author*

Scenario 1

Fig. 5.10 & 5.11 portray a scenario in which the collaborators (architect and the HVAC consultant) are present at geographically dispersed locations .i.e their respective office spaces. Fig. 5.10 shows a view of the architect's office where the architect can see a virtual avatar (in blue) of the HVAC consultant and the shared-augmented model of the building.

Remote Collaboration Scenario 1B

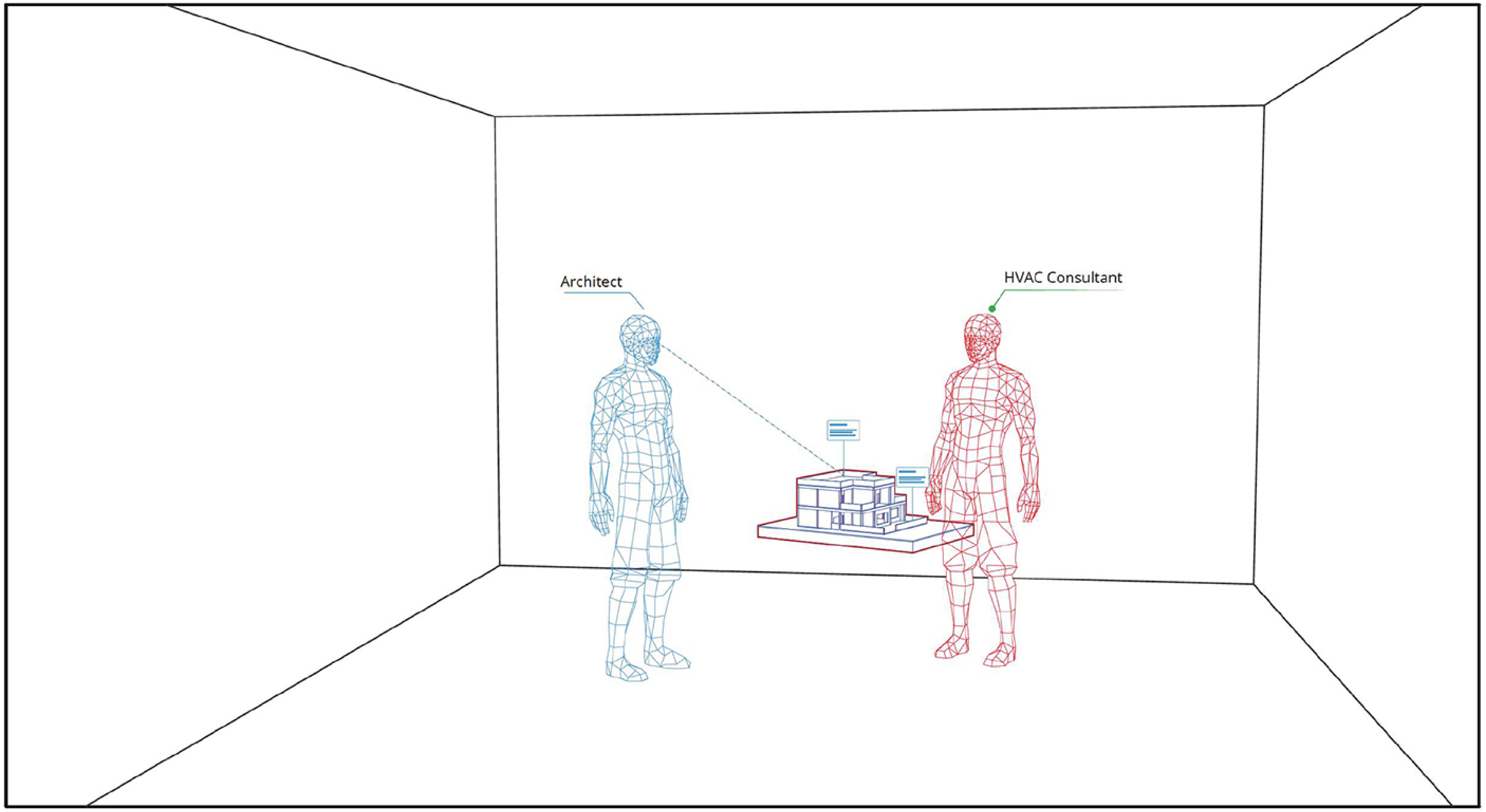


Fig. 5.11: *Office Space (HVAC) Remote Collaboration, Author*

Similarly, in Fig 5.11 the HVAC consultant can see a virtual avatar (in blue) of the architect and the shared virtual model of the structure.

Remote Collaboration Scenario 2A

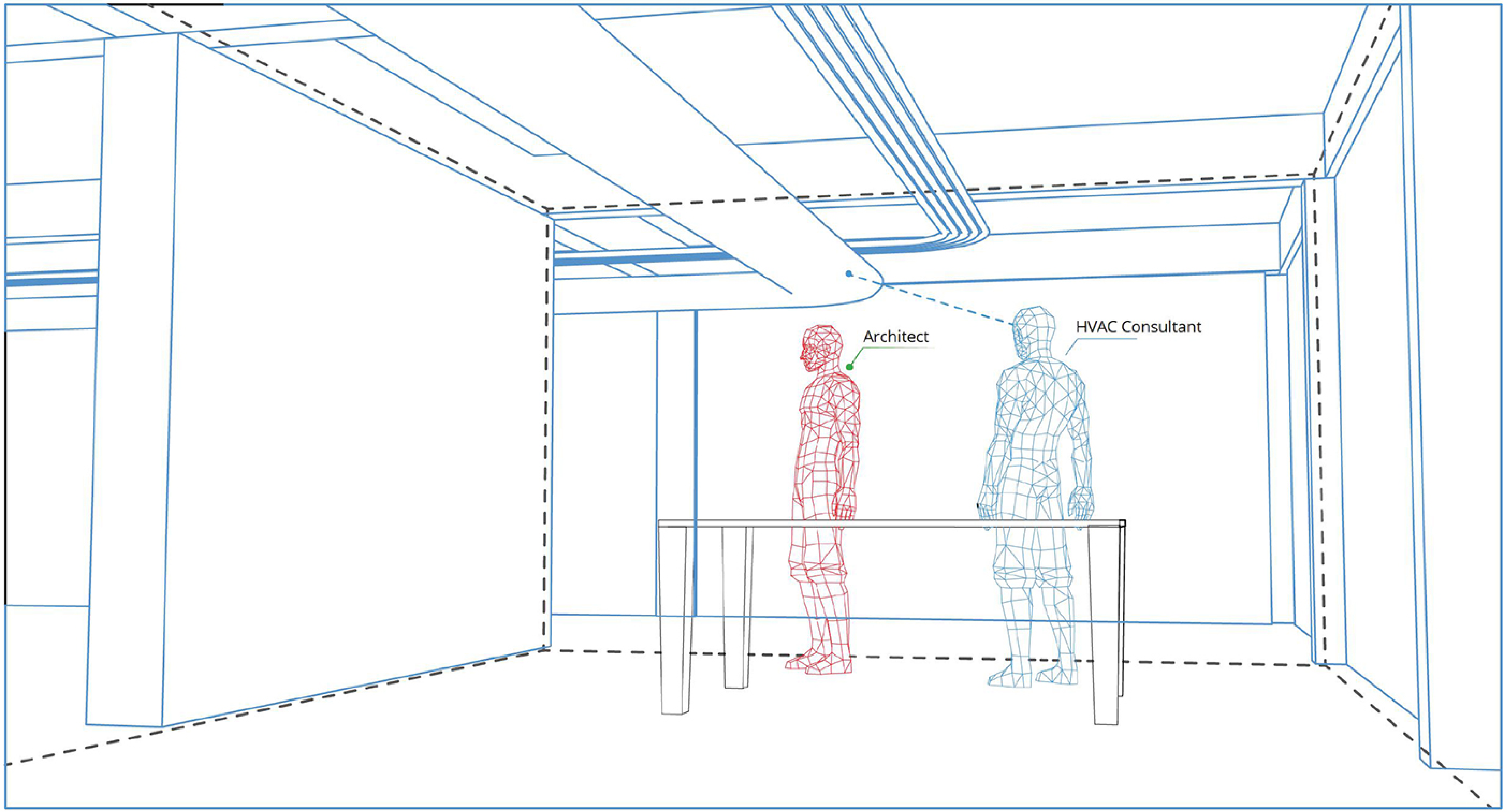


Fig. 5.12: *Office Space (Architect) Remote Collaboration, Author*

Scenario 2

Fig. 5.12 & 5.13 portray a scenario in which the Architect is present in an office space whereas the HVAC consultant is present at the actual site of construction. Fig. 5.12 shows the architect immersed in a 1:1 scale augmented model of the building where a virtual avatar of the HVAC consultant is also present in the virtual model. The location of the virtual avatar of the HVAC consultant is same as the location at the construction site.

Remote Collaboration Scenario 2B

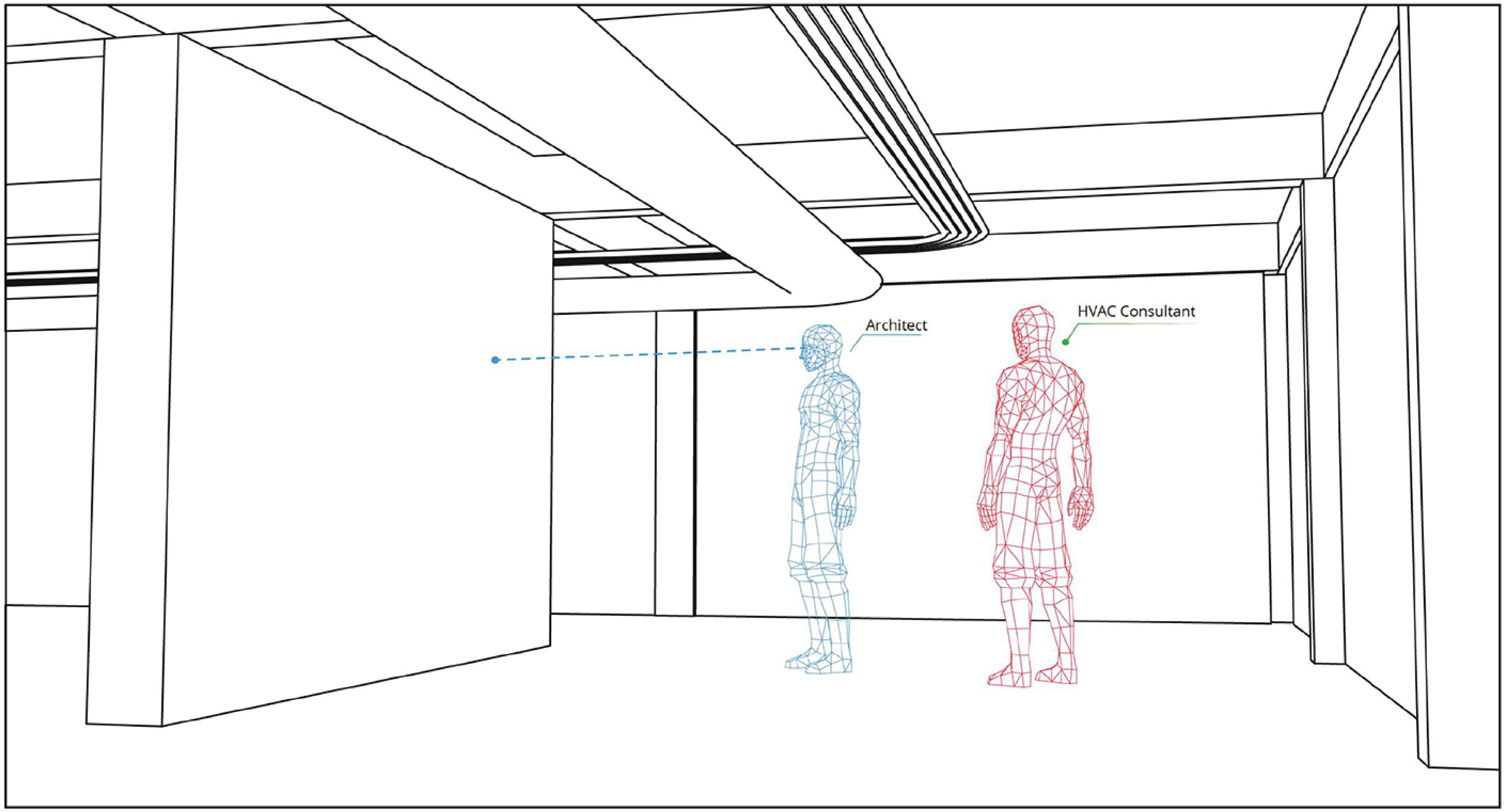


Fig. 5.13: *Construction Site (HVAC) Remote Collaboration, Author*

Similarly, at the construction site (Fig 5.13) a virtual avatar (in blue) of the architect is present as per the position in the virtual model of the building.

The designed scenarios illustrate the potential ways of using mixed reality as per the time/space matrix. Now that the scenarios, actors, and resources are defined, the next step was to identify the activities that are to be performed to manipulate the resources and also the tools to accomplish those activities.

5.4 Microsoft HoloLens

Hololens is an optical see-through, mixed reality Head Mounted Device. The target device for deploying the collaborative platform application was chosen to be HoloLens for a quite number of reasons as follows:

1. HoloLens is an untethered device with high processing capabilities which would allow the users to use the device anywhere without the need of an external processing unit.

2. Unlike mobile based AR devices, Hololens has technical advantages like spatial mapping, spatial understanding, spatial sound, gesture recognition, voice input, etc.

3. HoloLens being a stand-alone device would deliver the same experience to all the users.

4. Since HoloLens is an HMD, it is hands-free and would allow working while wearing the headset.

Fig. 5.14: *Microsoft Hololens*

HoloLens Input Modalities

Gaze, Gesture, and Voice are the three input modalities on which Hololens works

1. Gaze
The gaze point is primarily the focus area of the user.

2. Gesture Input
Hololens recognizes six predefined hand gestures. Using these gestures one can interact with the virtual elements.

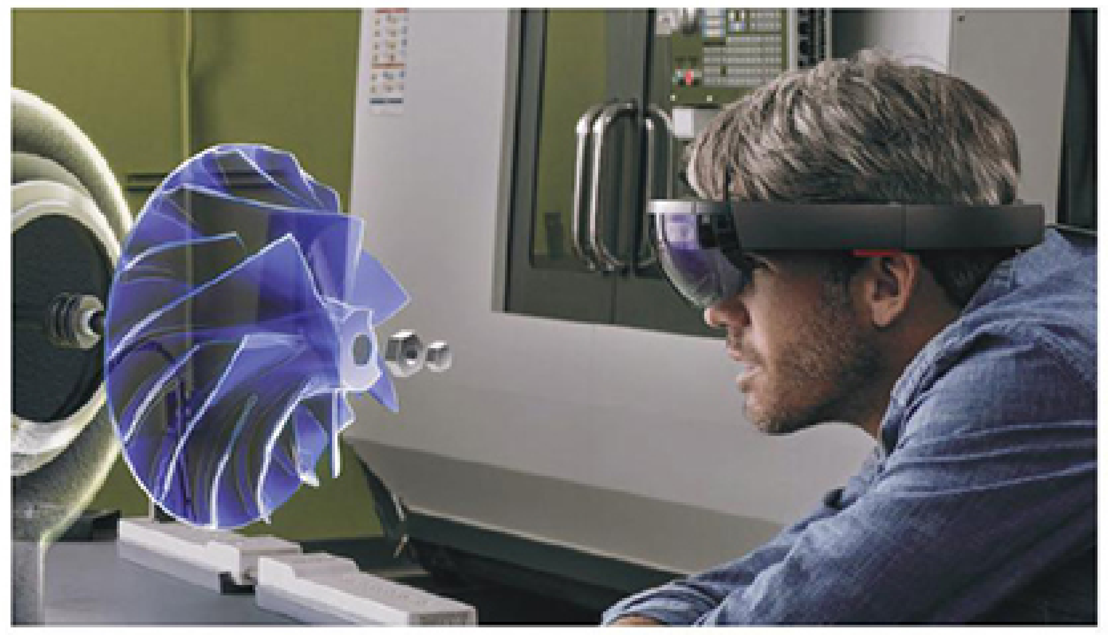


Fig. 5.15: *Mixed reality view, Microsoft HoloLens*

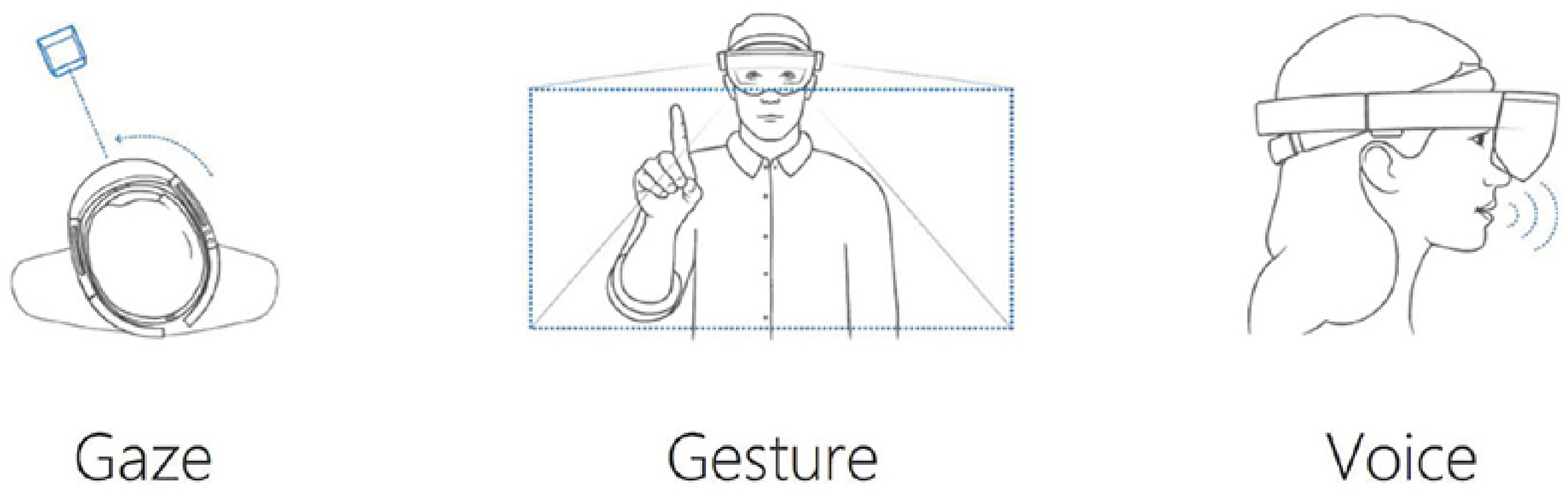


Fig. 5.16: *HoloLens input modalities, Microsoft*

- AirTap Gesture
- AirTap + Hold + Free Drag
- Air Tap + Hold + Horizontal Slide
- AirTap + Hold + Vertical Slide
- Airtap (Both Hands) + Hold + Stretch
- Bloom Gesture

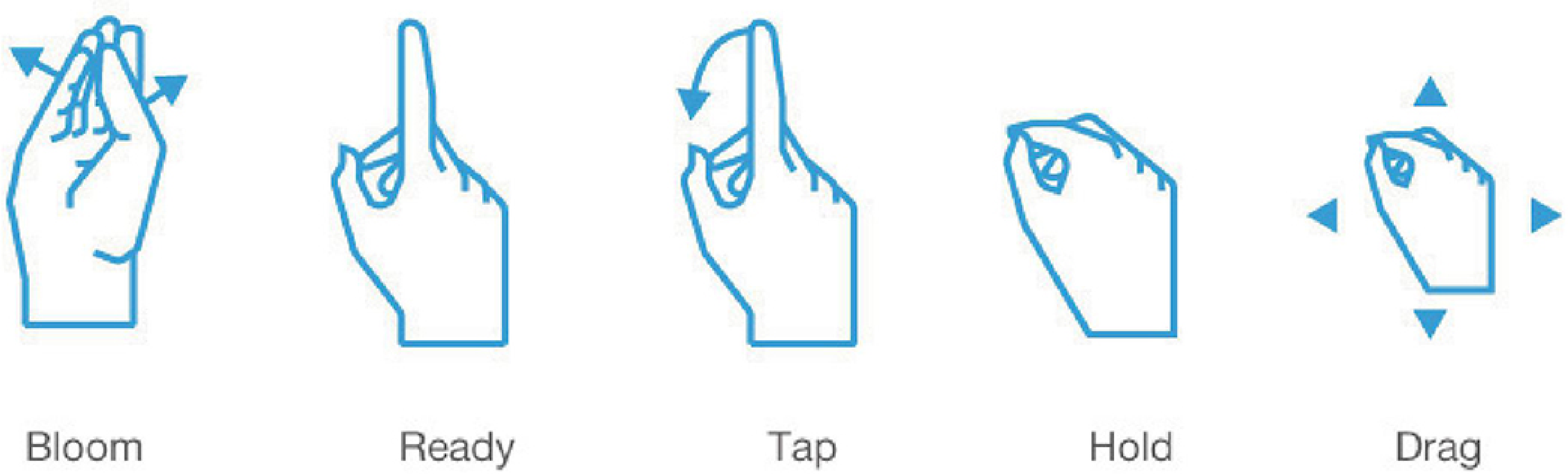


Fig. 5.17: *HoloLens hand gesture input, Microsoft*

3. Users can also give voice commands to trigger events.

5.5 Activities

An activity is a group of tasks performed to manipulate the shared resources either directly or by aiding in other collaborative activities. In our context, the primary resource is the augmented 3D model of the building. We identified collaborative activities based on

- Modification activities
- View-ability activities
- Communicative activities

1. Modification activities
Modification activities group contains the activities which allow the user to manipulate the shared resources. The shared resource in our context is a 3D model of the building. Following are the modification activities primarily based on how manipulation works in a 3D software

- Adding 3D elements like walls, furniture, ducts, beams, columns, etc
- Deleting/removing existing 3D elements from the model
- Moving/altering the position of 3D elements in 3 vectors
- Rotating the 3D elements in 3 vectors
- Scaling the 3D elements: 1-D, 2D, Uniform, Planer
- Changing color and material of the elements

2. Viewability activities
View-ability activities aid the user to perceive the 3D model and other information quickly and effectively. View-ability activities would allow the user to do the following

- Change layer Visibility
- Change layer Opacity
- Scaling the full model
- Adding section/clipping plane
- Moving and Rotating section/clipping plane

3. Communicative activities

This group of activities enhances the communication between the collaborators. Following are the activities

- Adding annotations
- Drawing in 3D
- Change object color on selection
- Adding supplementary elements like photos/ videos/ drawings

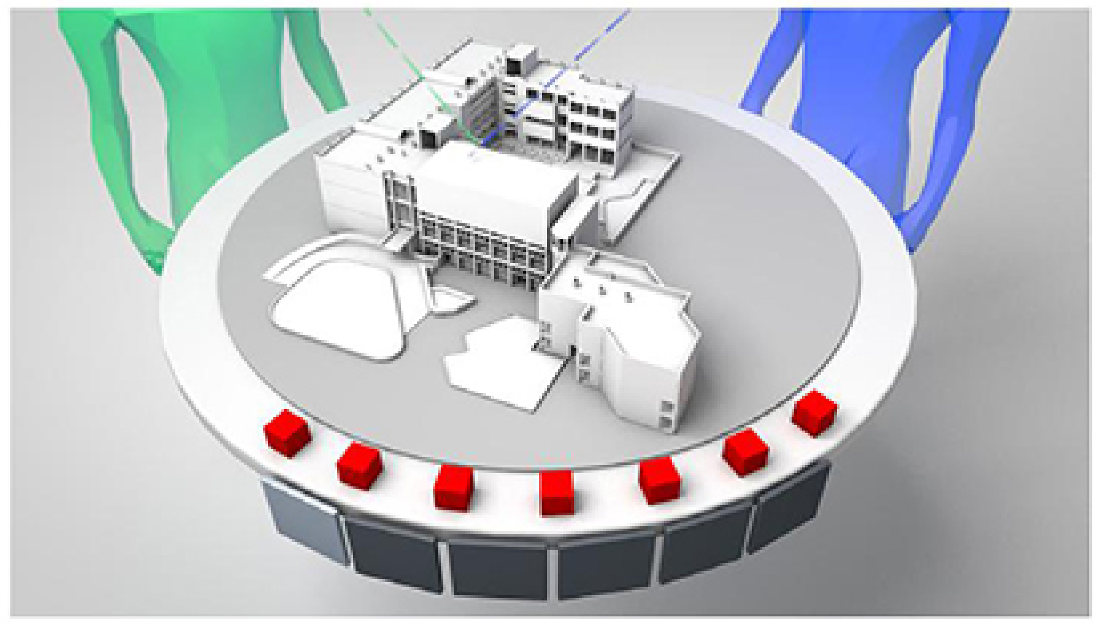


Fig. 5.18: *Collaboration station, Author*

5.6 Spatial Interface

The whole interface of the platform sticks in and around a circular table called the collaboration station. The main menu wrapped around the collaboration station revolves around the table and is always facing the user. The collaboration station holds two significant parts of the interface. We divided the tabletop into two concentric circles. The inner circle hosts the 3D model of building and the outer circle hosts the submenu items.

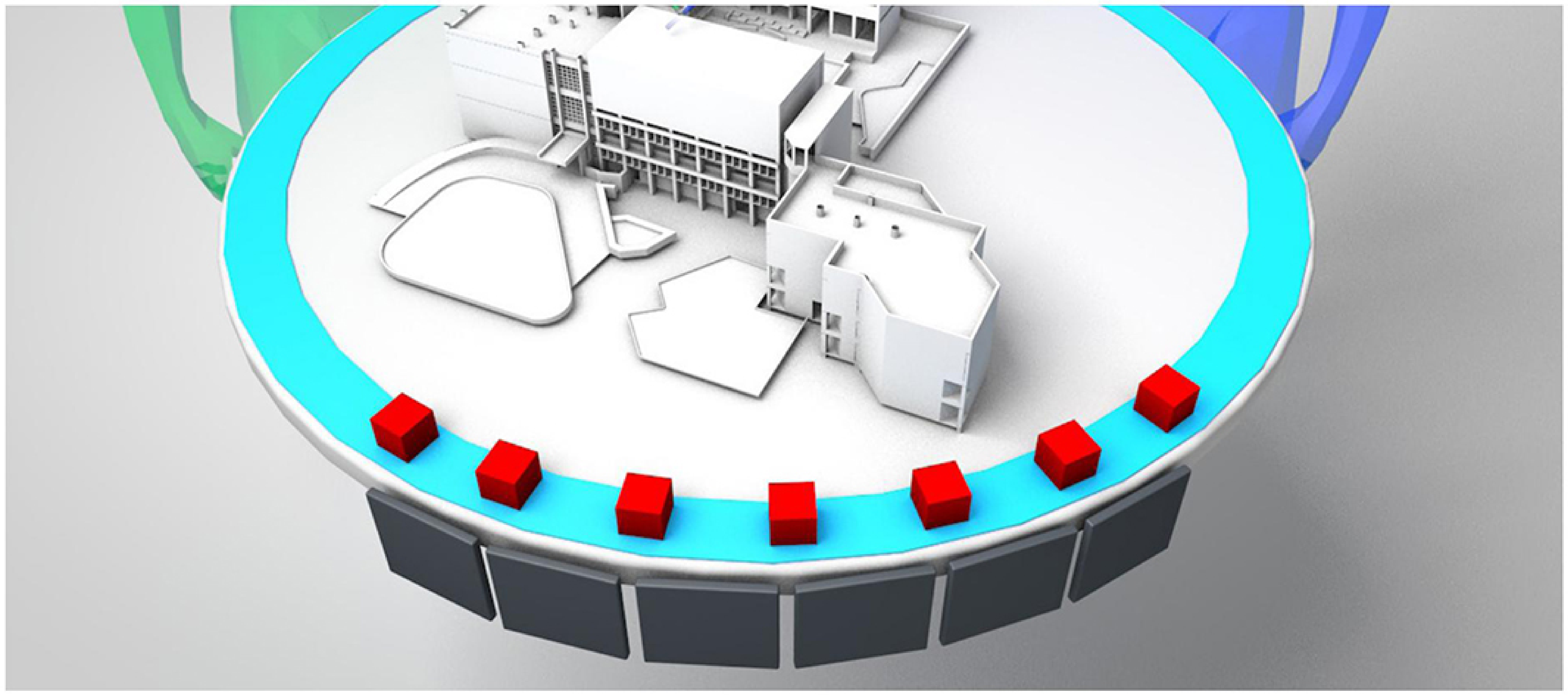


Fig. 5.19: *Collaboration station; Submenu (outer ring), Building 3D model (inner ring), Main menu (wrapped around the station), Author*

5.7 Interaction Design for activities

The interactions for the identified activities were designed using the hand gesture inputs provided by Hololens as per the requirements for our context.

Modification Interactions

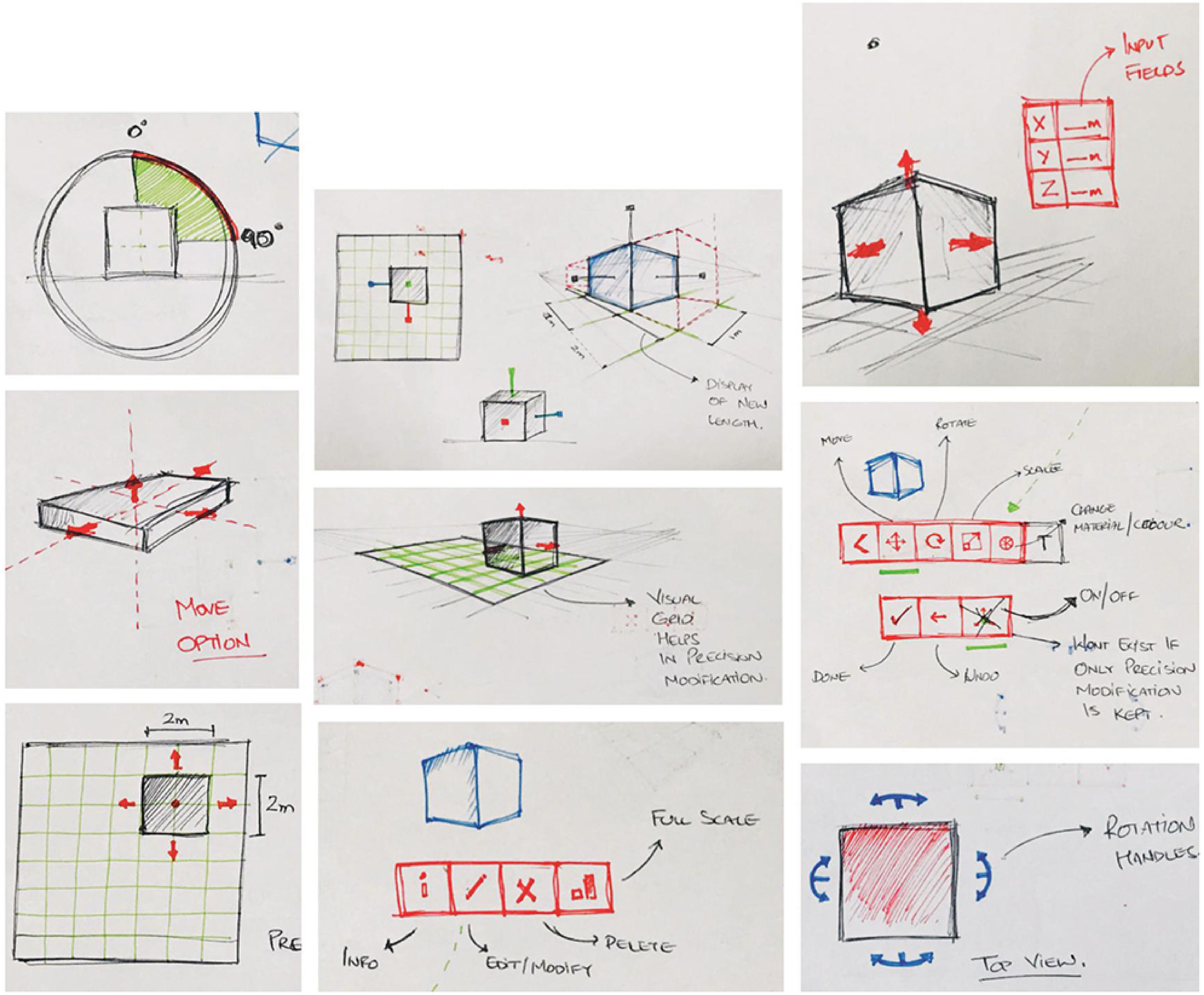


Fig. 5.20: *Different modification interaction explorations, Author*

1. Adding and Placing an element

The collaborators can add pre-defined 3D components to the existing 3D model of the structure. These elements include 3D models from different disciplines like Architecture, Structure (beams, columns, footing, etc.), Plumbing, HVAC, Electrical, etc.

For adding an element, the user needs to select one from the different categories of the disciplines available. Depending on the placement, the scale of the element changes from for, e.g., 1:500 (scale of the 3D model) to 1:1. If the element is placed out from the boundary, the scale is changed to 1:1, and if placed inside the model the scale of the element becomes as of the model, i.e., 1:500. The element casts a shadow on the surface below which indicates the space that element will occupy upon placement.

Input used

• AirTap + Hold + Free Drag

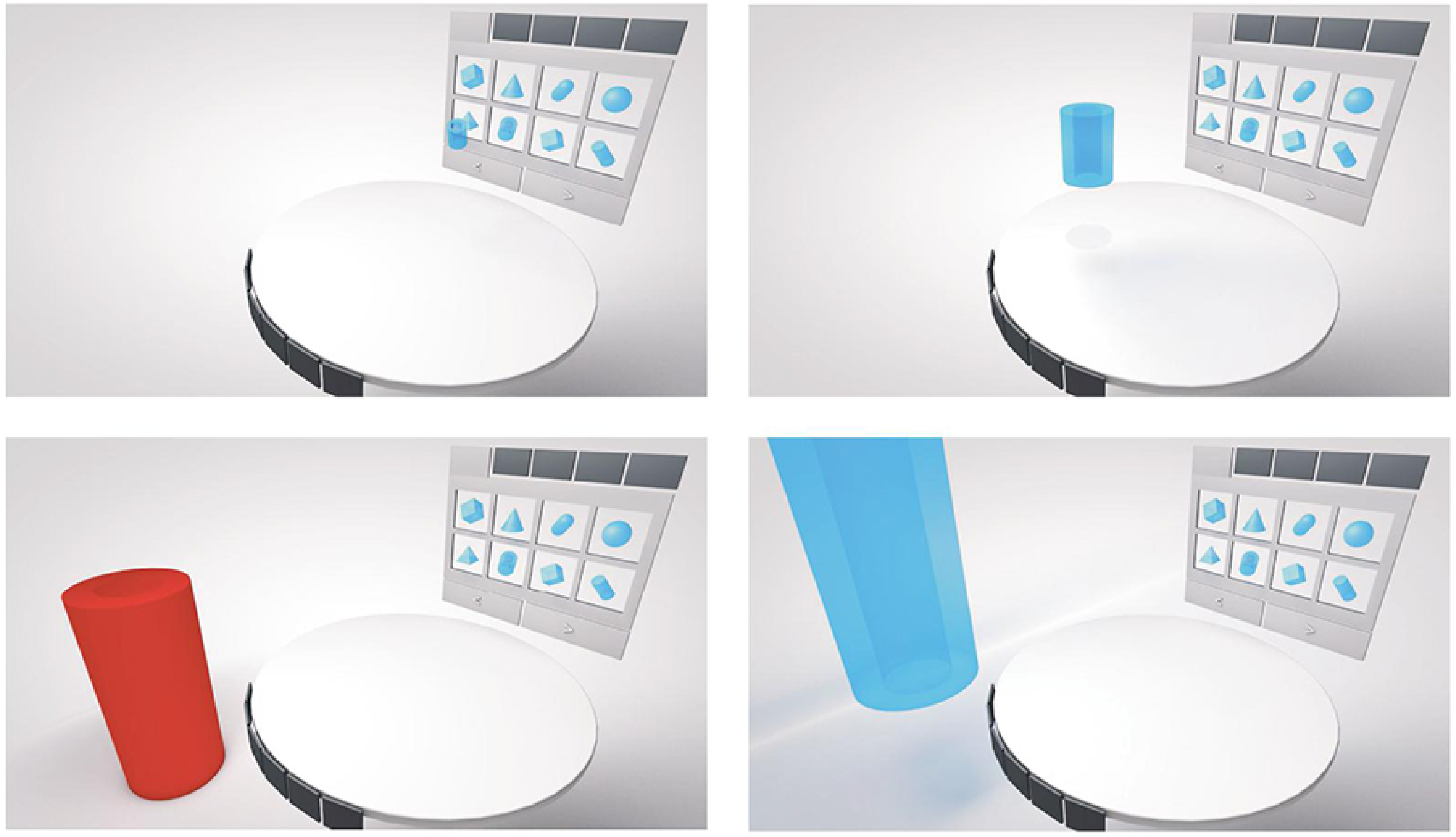


Fig. 5.22: *Sequence images (clockwise), Adding and element and placing it outside the station area, Author*

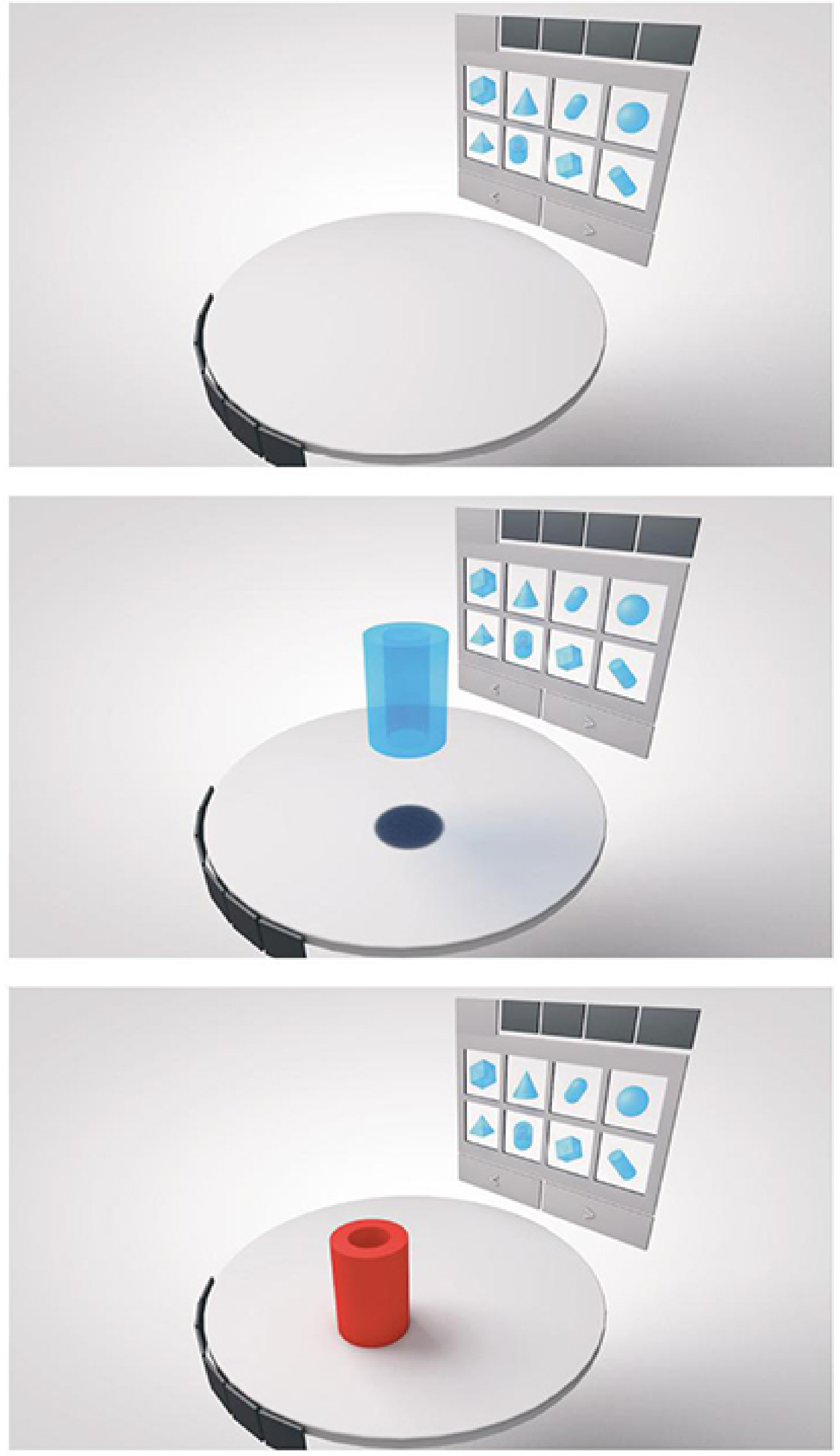


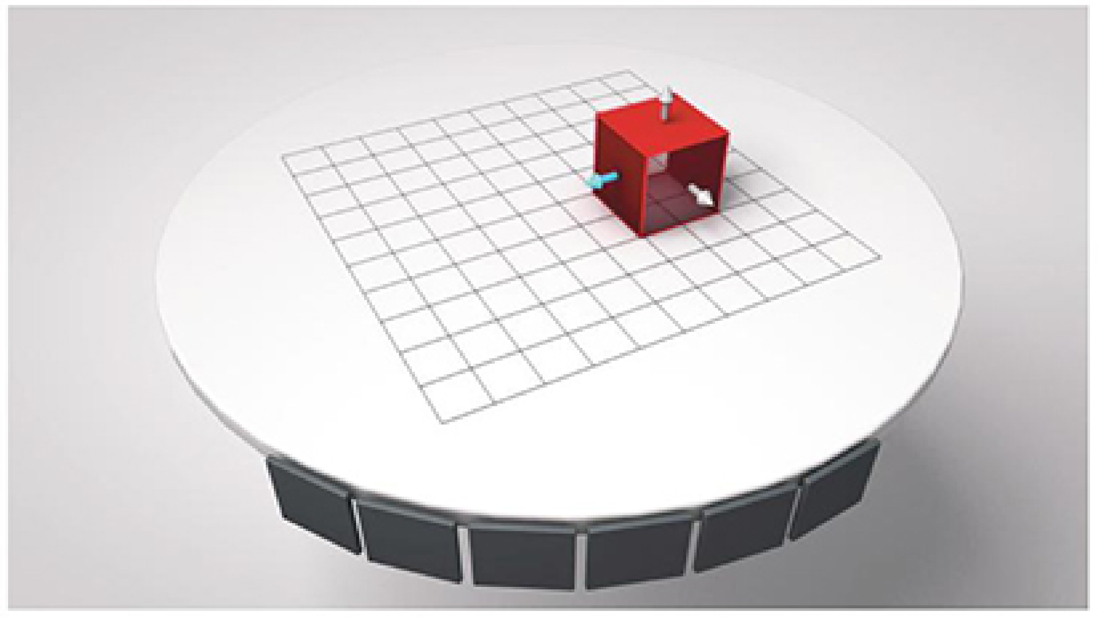
Fig. 5.21: *Sequence images (Top to Bottom) Adding an element and placing on the table Author*

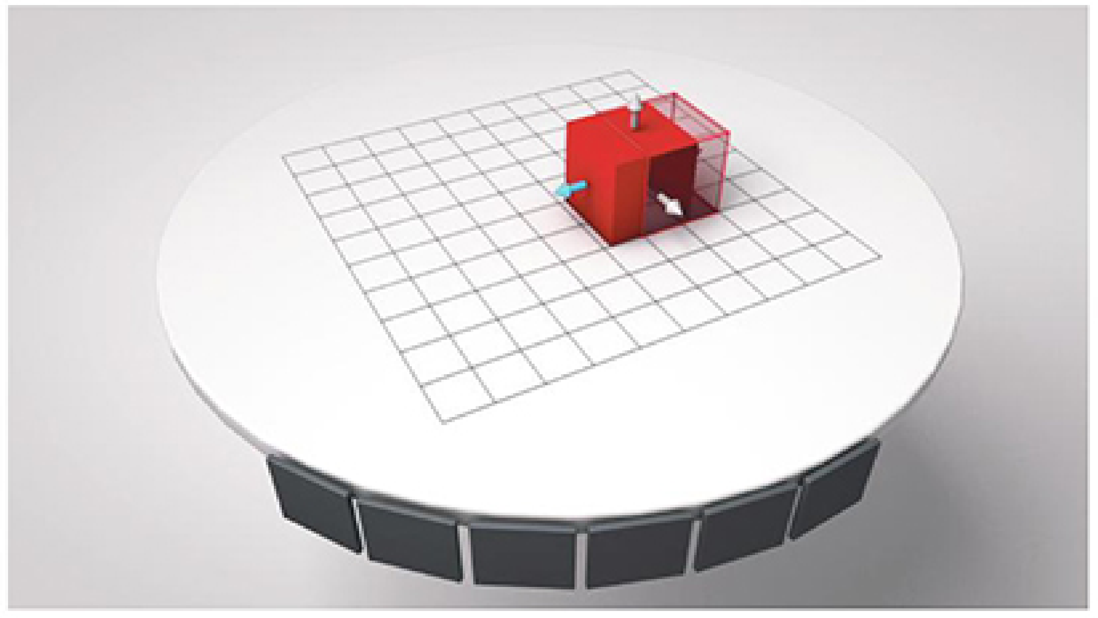
2. Deleting/removing an existing element from the model
The collaborators can remove the desired elements from the structure.

For deleting an existing element, the user needs to select an element from the model. After an element is selected, the user can delete the object by choosing Delete from the pop up menu

3. Moving/altering the position of 3D elements in 3 vectors
The collaborators can move the elements either freely or by selecting a vector (arrows around the element) among x,y & z to move the object in the vector direction chosen. In the architectural context, these movements are well thought off and are measured.
A grid appears parallel to the direction of movement of the object, to give an idea of the displacement. A ghost object stays on the original position until the selected element is displacing. The distance between the ghost object and the actual object is displayed while the element is undergoing displacement.

Inputs used
•Gaze + AirTap
• AirTap + Hold + Horizontal/Vetrical slide





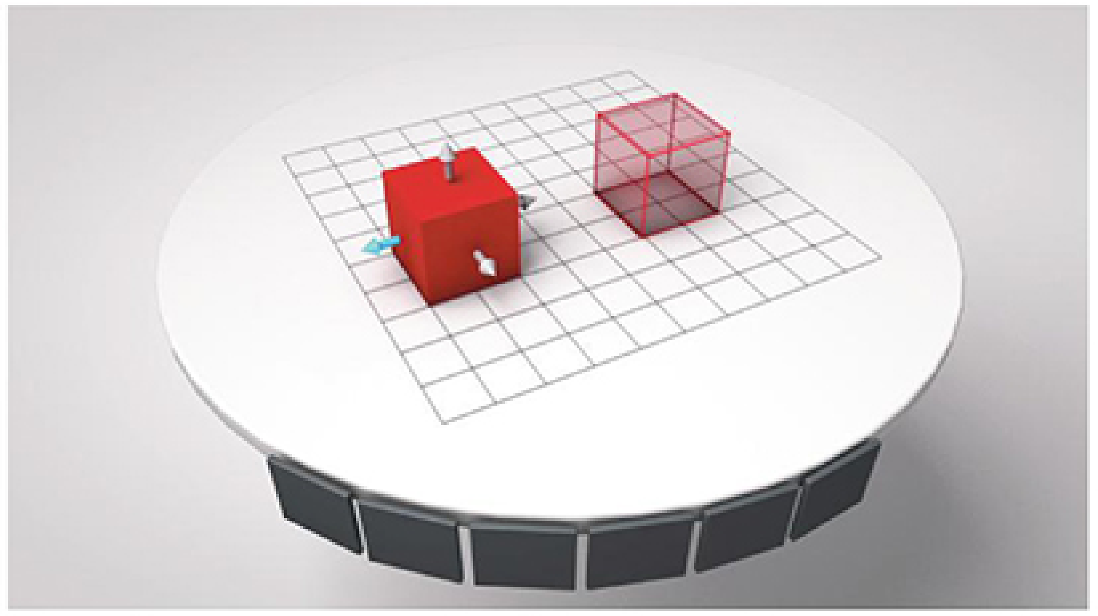


Fig. 5.23: *Sequence images (Top to Bottom) Moving an element, Author*

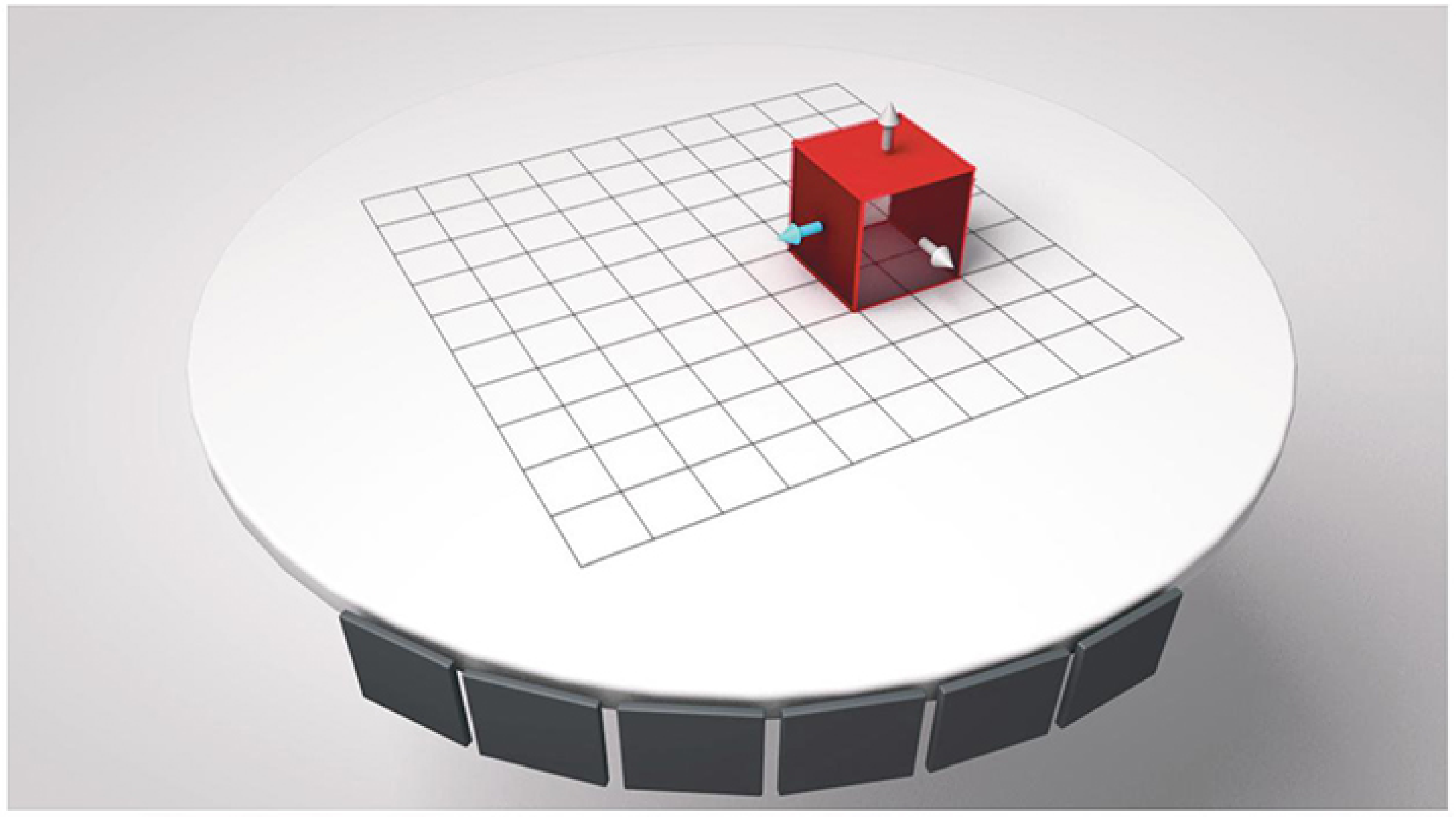


Fig. 5.24: *Axis handles (blue and white) for moving an object, Author*

4. Rotating an element

Rotating an element is similar to the movement interaction. The user can select the rotation handle for rotating the object in the chosen vector direction. A radial grid parallel to the rotation direction shows the angle the object has turned from the initial position.

The user can also select a particular vector to input the desired angle of rotation.

Inputs used

•Gaze + AirTap
• AirTap + Hold + Horizontal/Vetrical slide

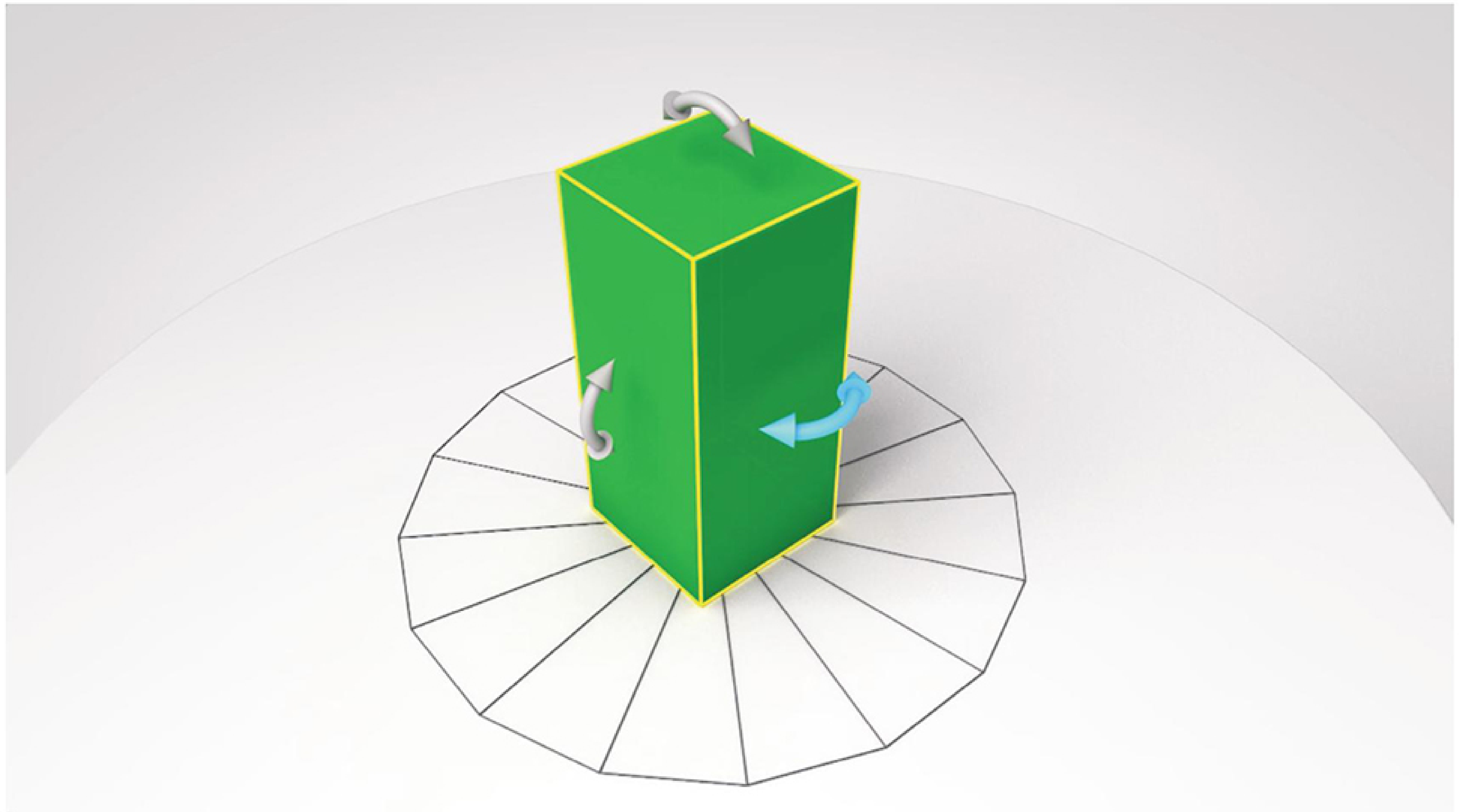


Fig. 5.25:
Rotation handle and reference grid

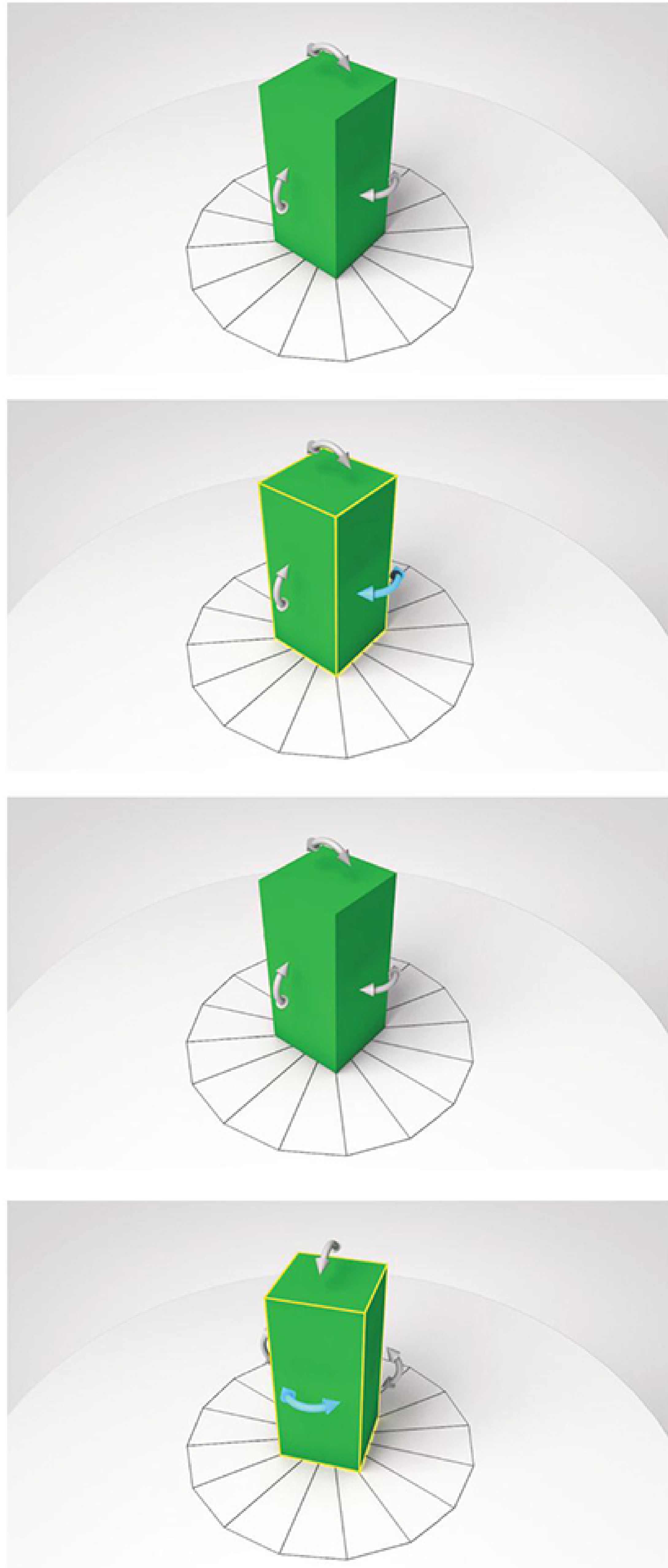


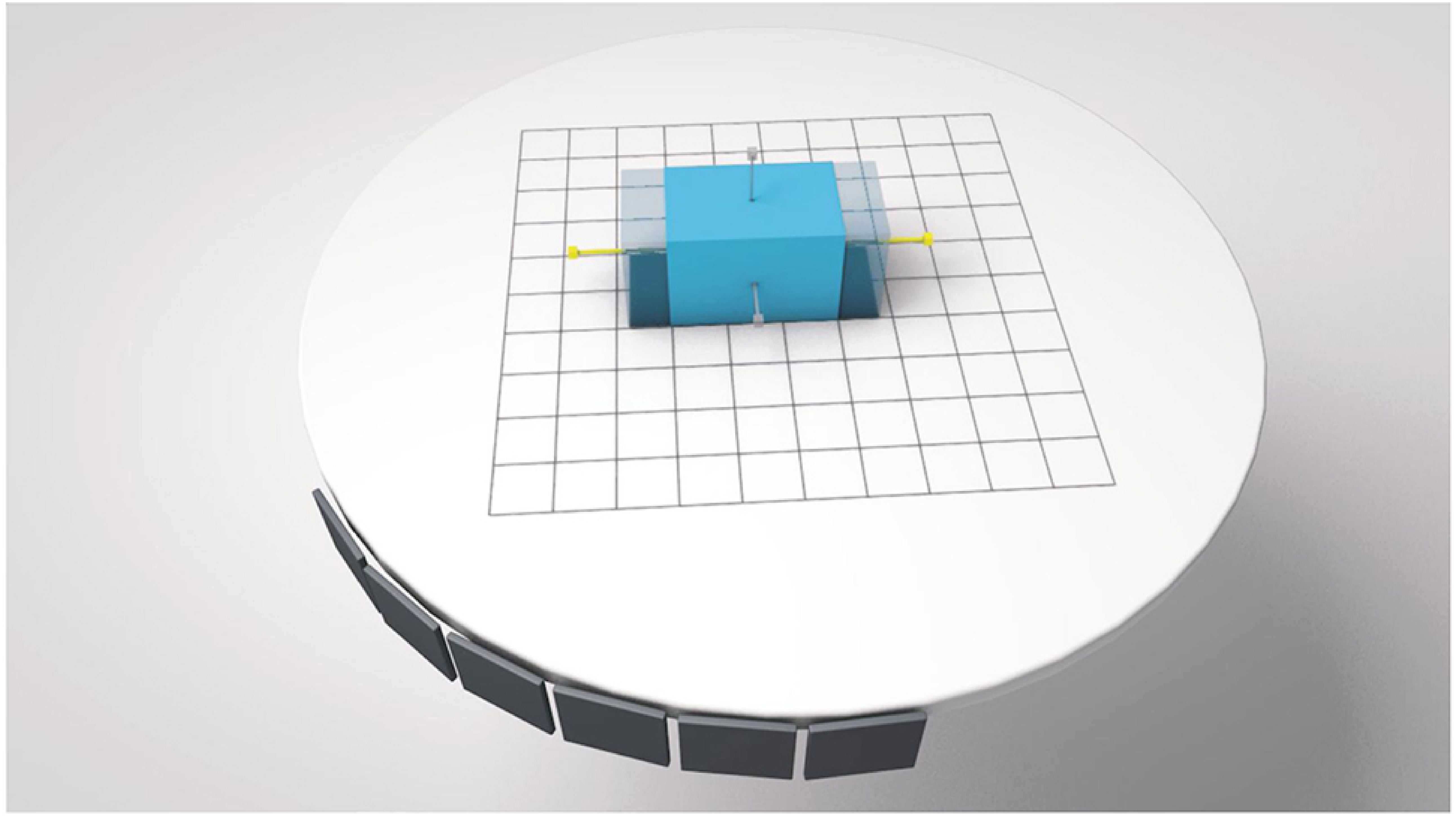
Fig. 5.26: *Sequence image (Top to Bottom)*
Rotating an element using rotation handles.

5. Scaling an element

Scaling can be 1 Dimensional, 2 Dimensional or Uniform. Vector handles appear around the object and by using the handles the user can scale the element in 1D or 2D. When scaling, a grid appears for reference, and the scaled object appears in ghost mode, and the original element stays as it is until the scaling is happening. It allows the user to get a reference to the difference between the initial and the final scale of the element.

Inputs used

•Gaze + AirTap
• AirTap + Hold + Horizontal/Vetrical slide
• AirTap (Both hands) + Hold + stretch



6. Changing Material and Colour

Collaborators can change the color and materials of the selected object using pre-defined materials or by using the color wheel.

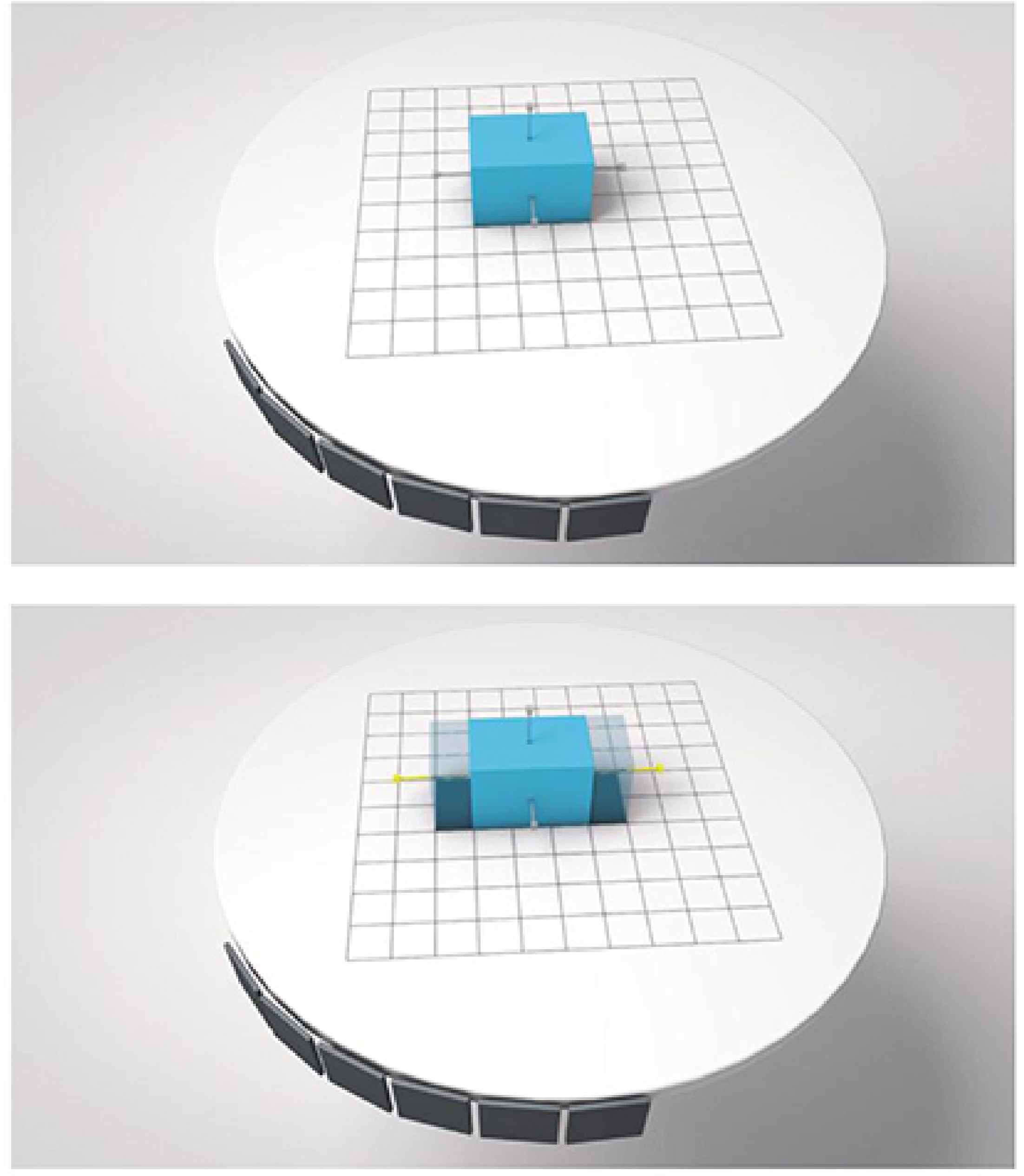
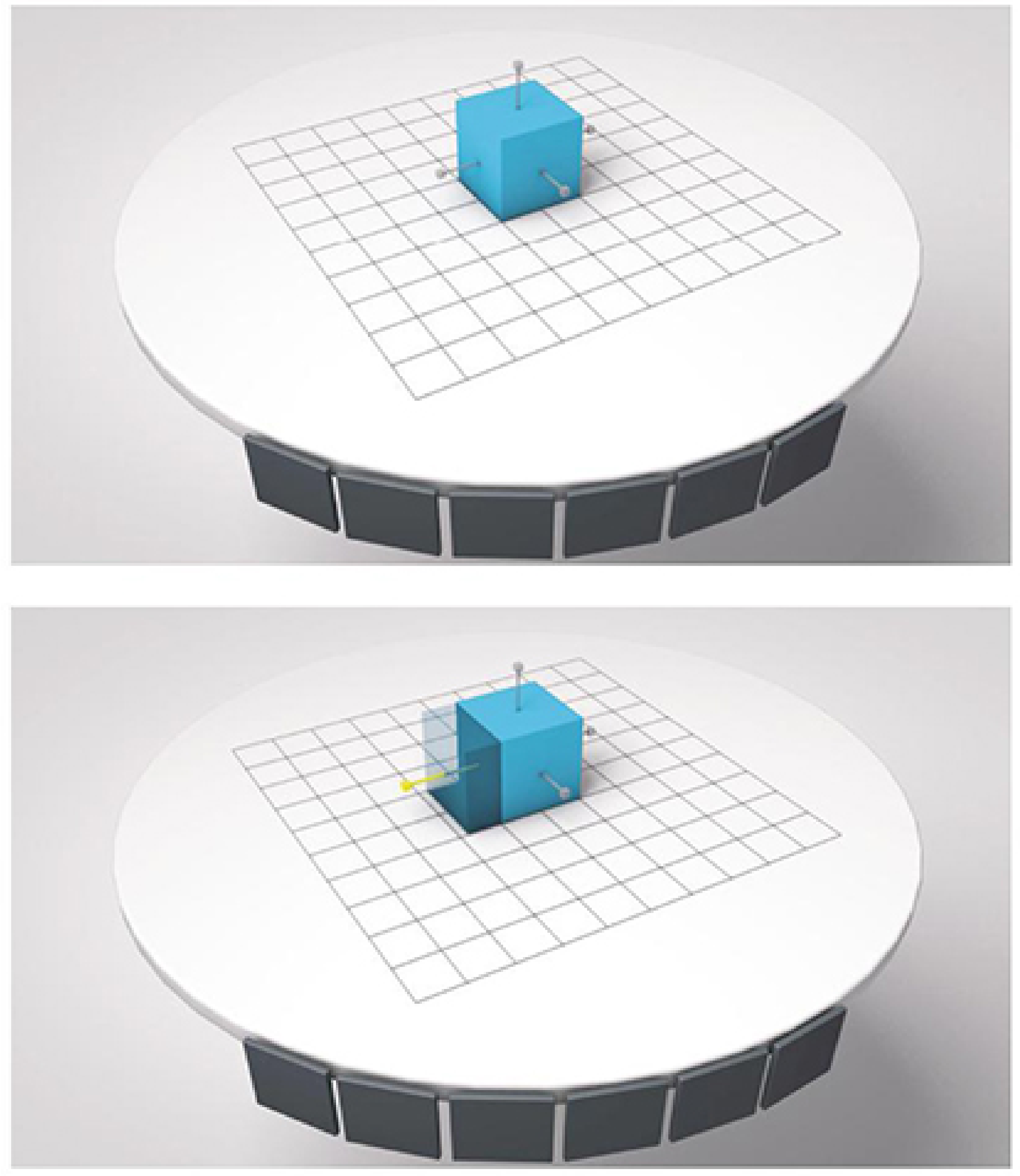
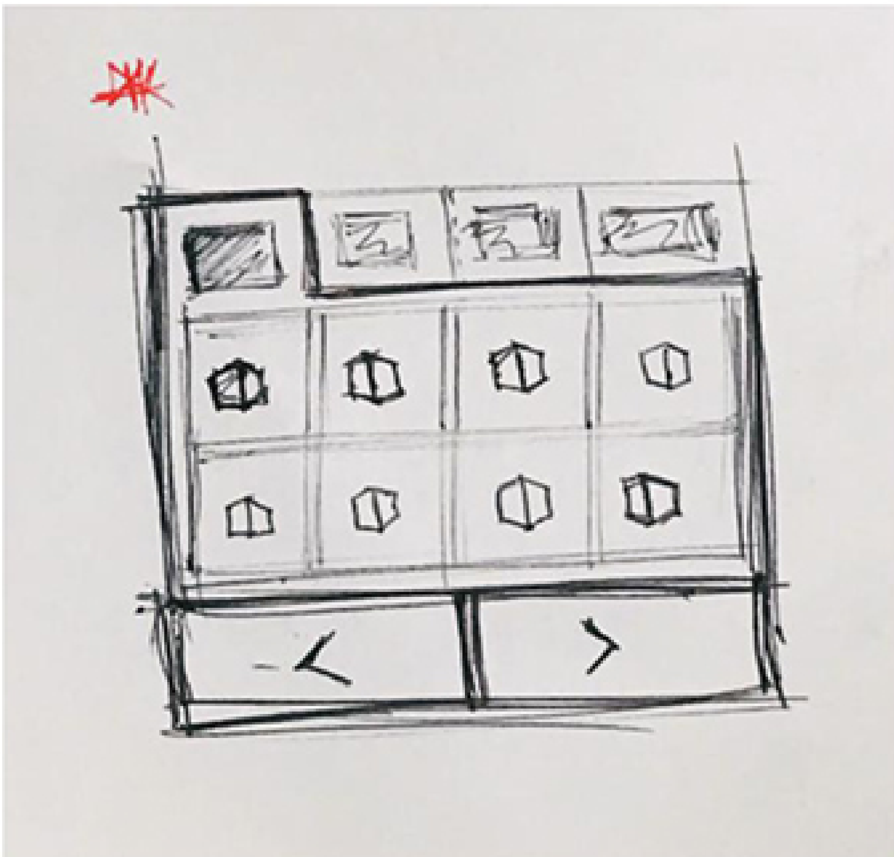


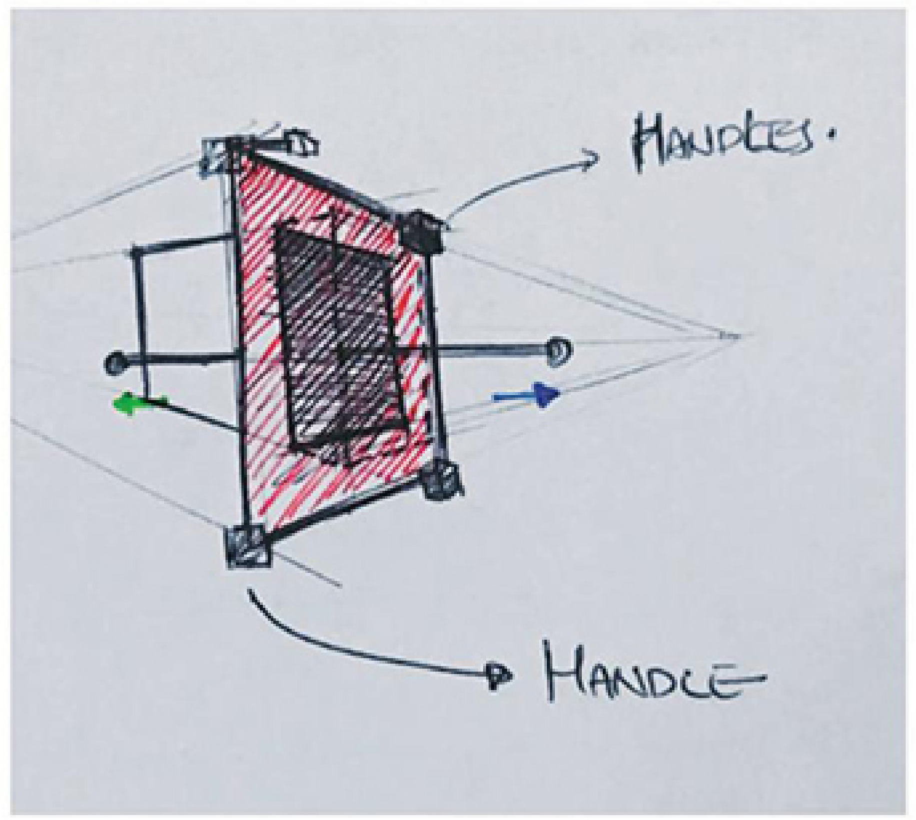
Fig. 5.27a: *Scaling 1D, Author*

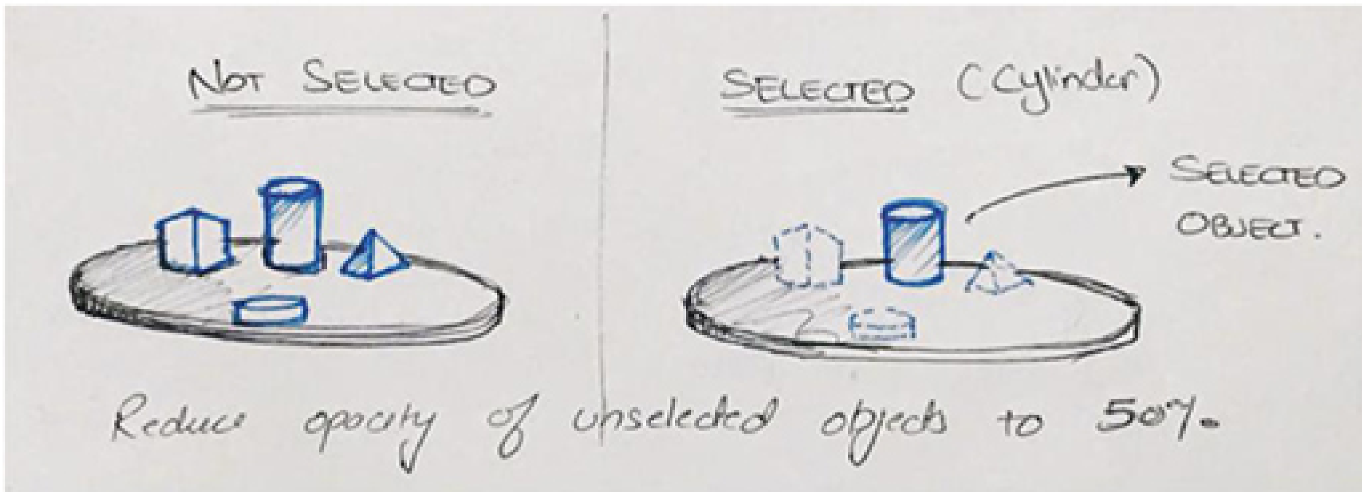
Fig. 5.27b: *Scaling 2D, Author*

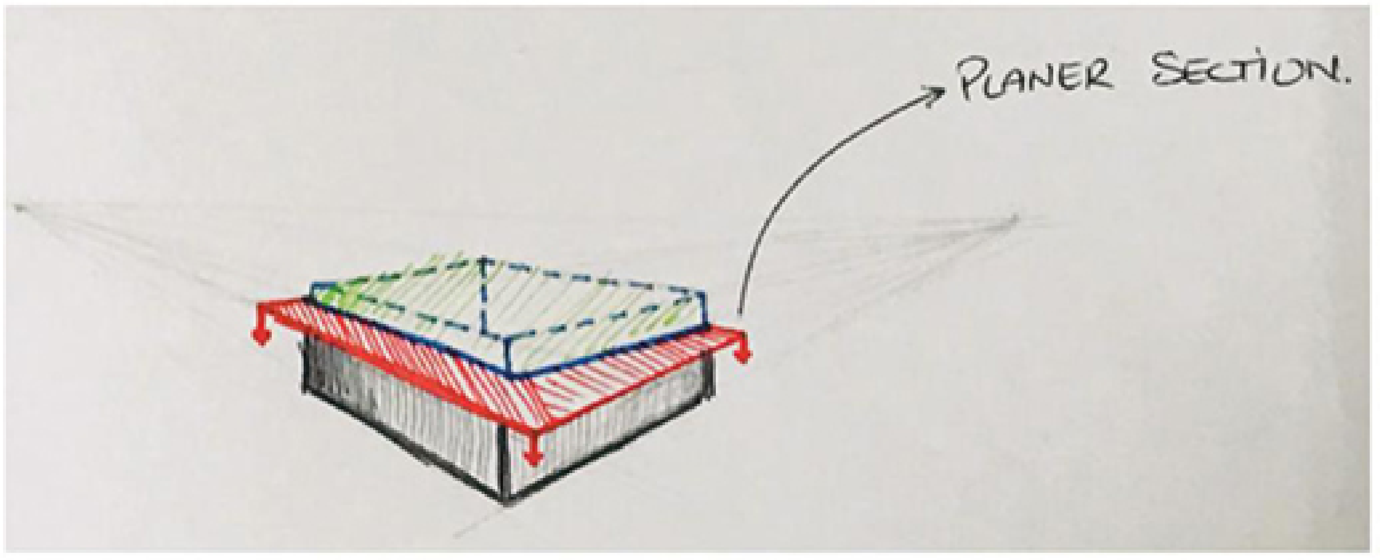


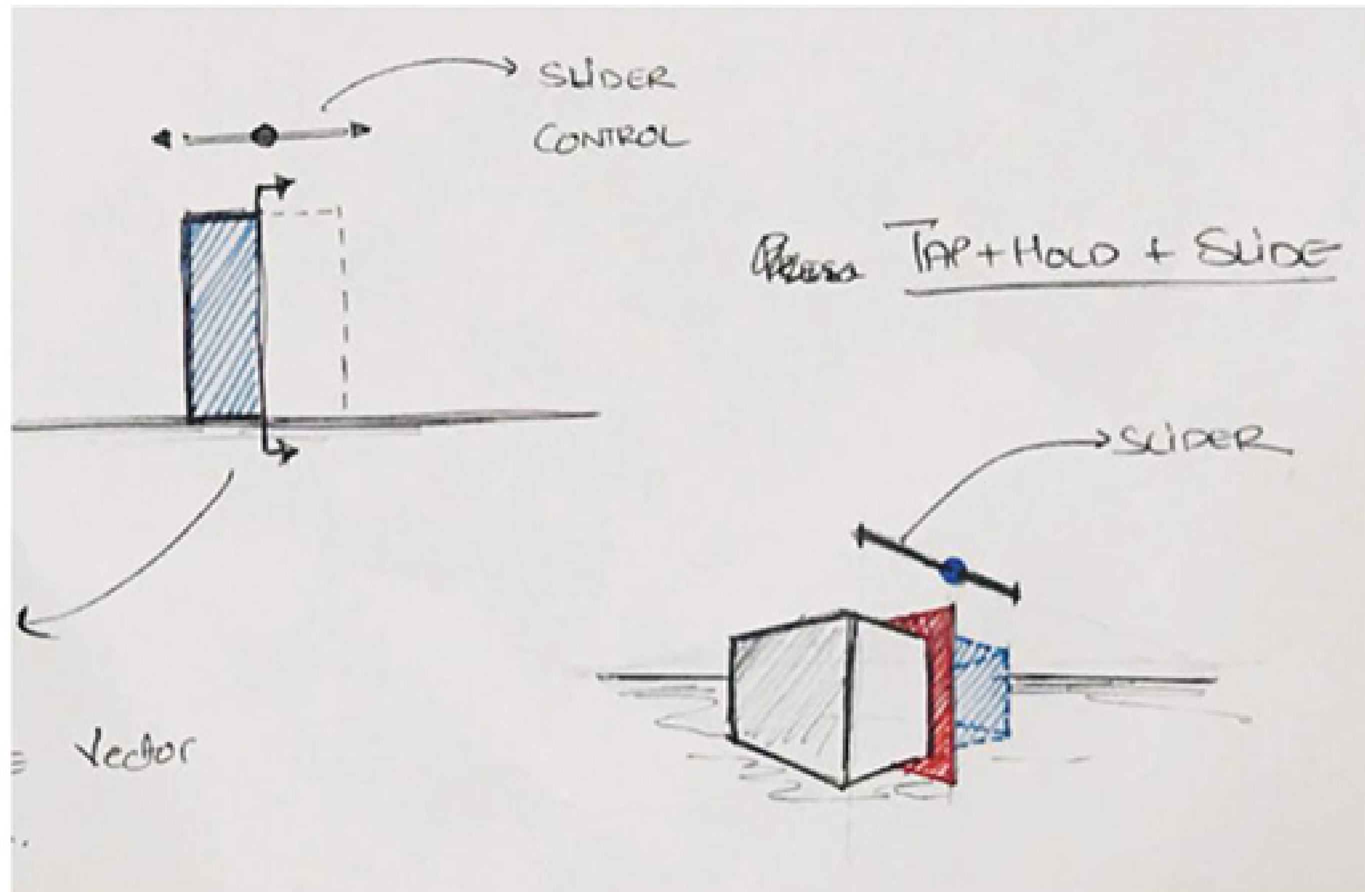
Viewability Interactions

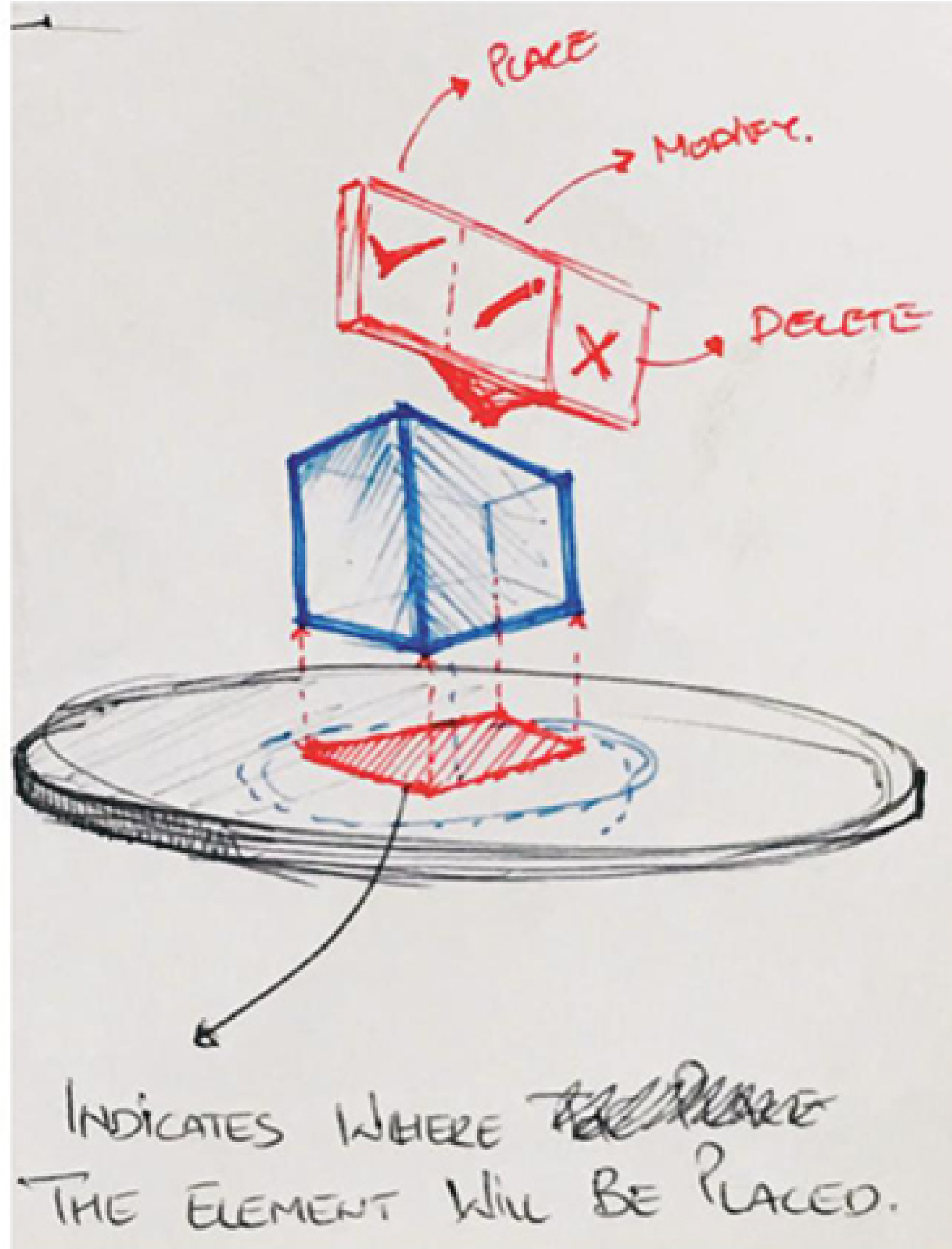


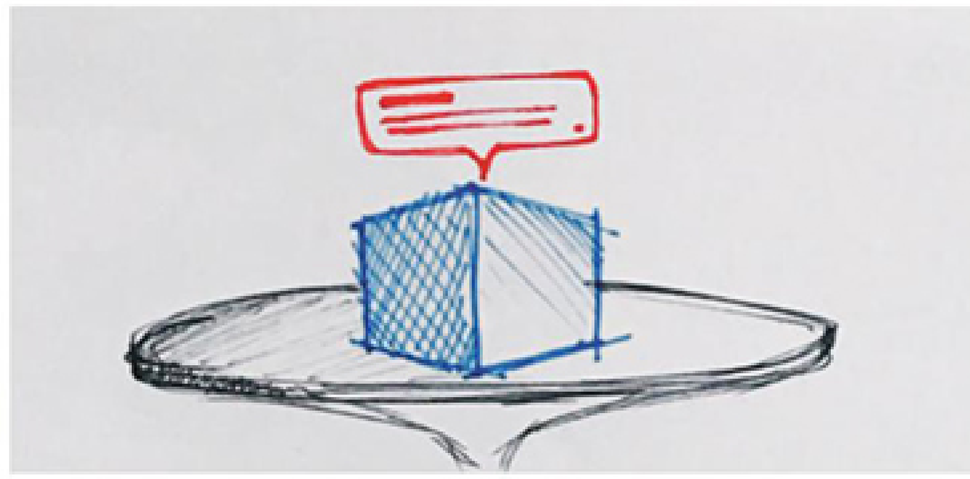


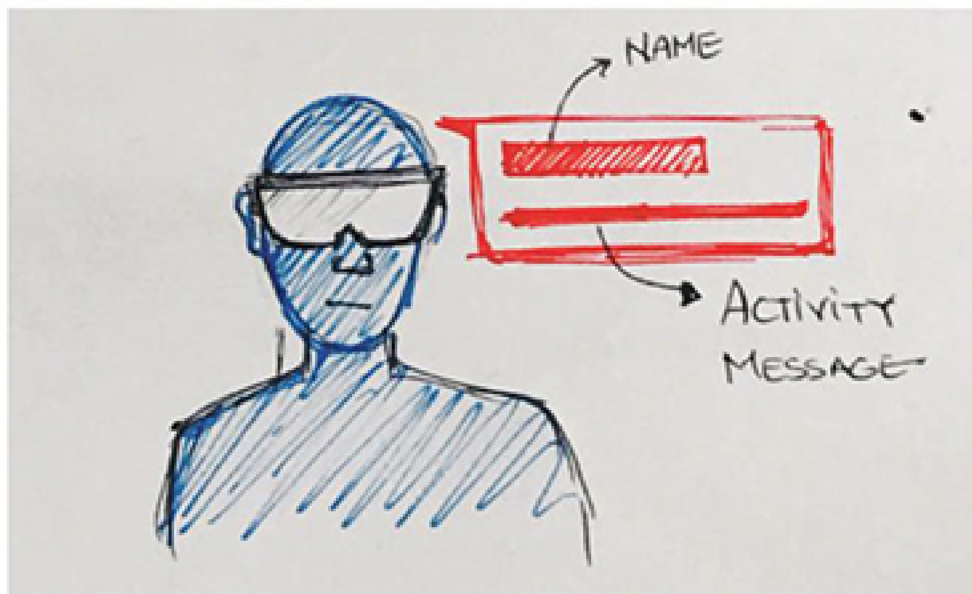












1. Layer Visibility

An architectural model contains different layers like for, e.g., architecture, structure, HVAC, etc. To focus on a specific layer either a layer is isolated by turning off the visibility of all other layers except the selected one or by turning off any particular layer. The collaborators can change the layer visibility while performing specific activities. The visibility remains same for all the users.

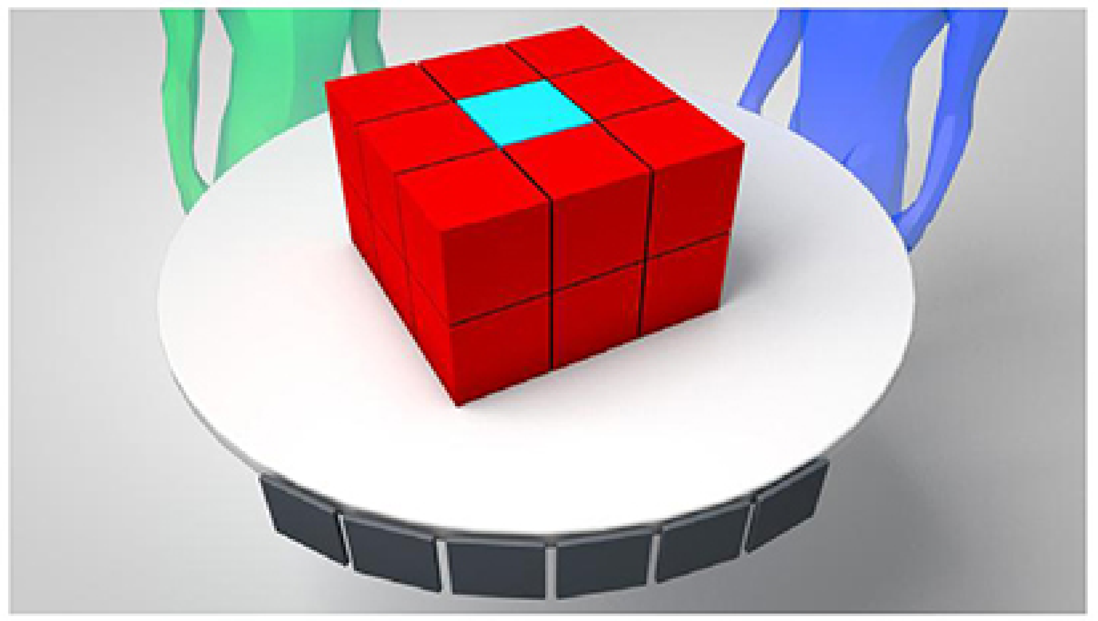


Fig. 5.28: *Red & Blue layer active*

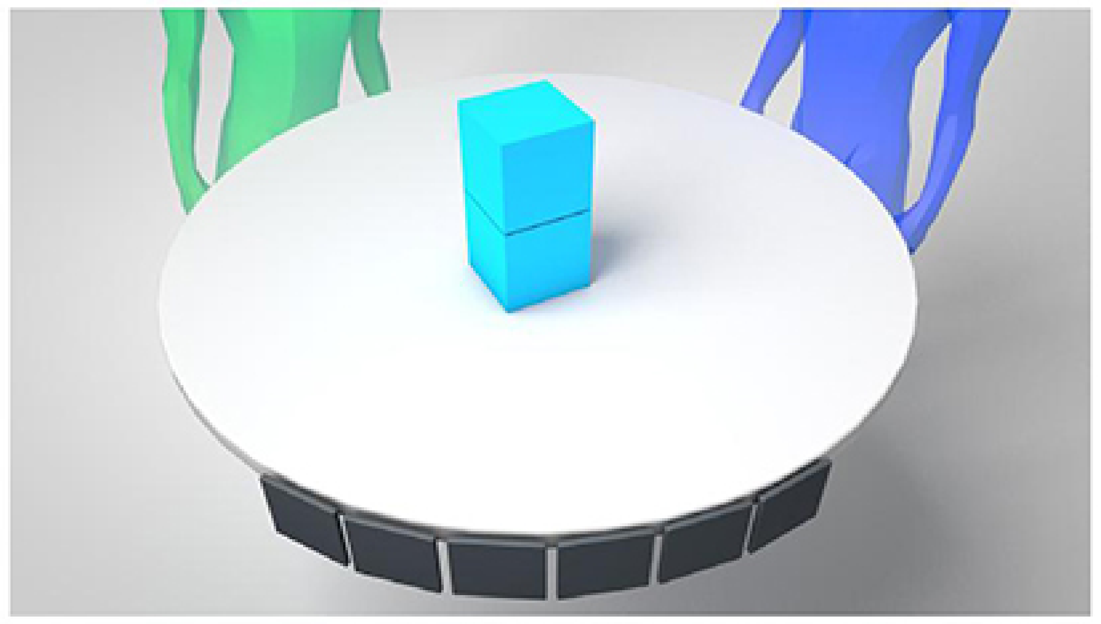


Fig. 5.29: *Blue layer Isolated*

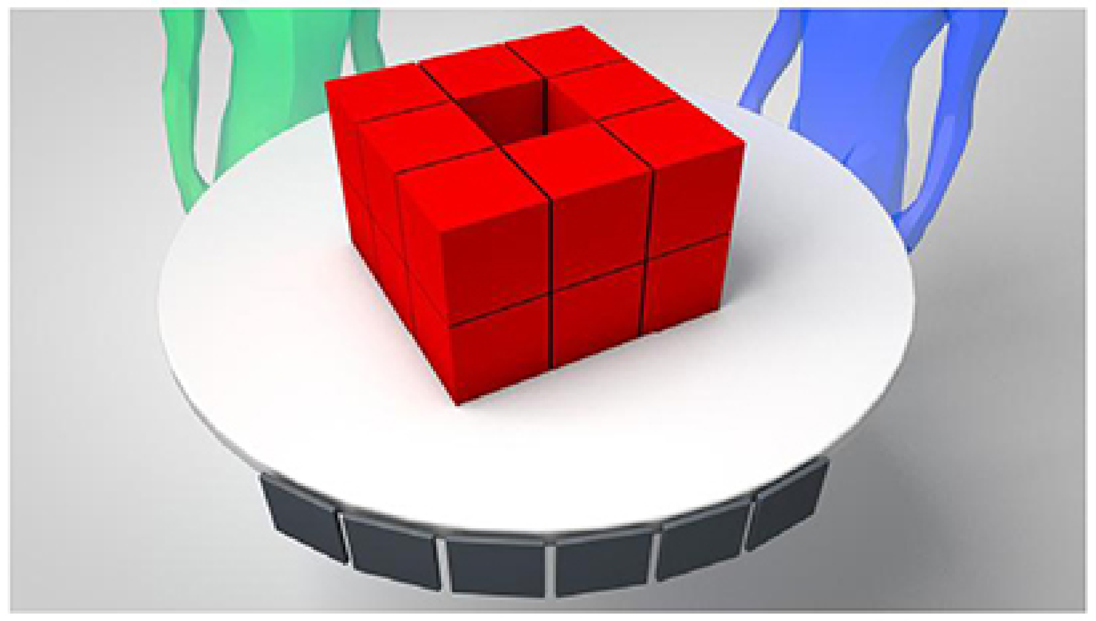


Fig. 5.30: *Blue layer Off/ hidden*

2. Layer Opacity

At times, the user wants to focus on the objects in a particular layer A but, concerning another layer B which is hindering the visibility of the layer A. Opacity-toggle allows the user to reduce the opacity of the selected layer or all other layers except the selected one.

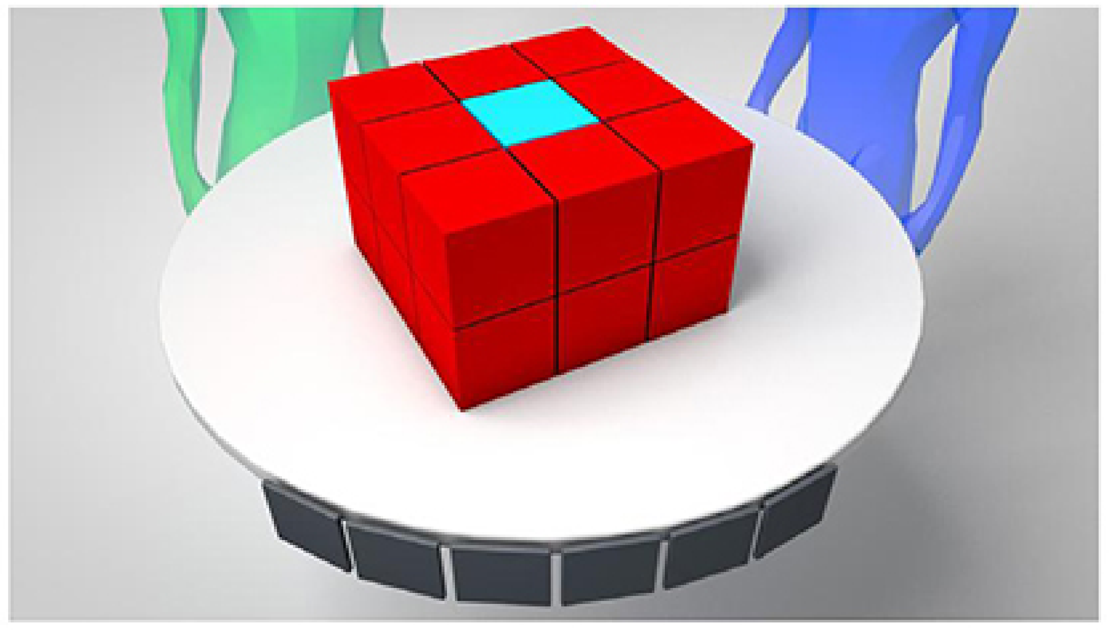


Fig. 5.31: *Red & Blue layer active*

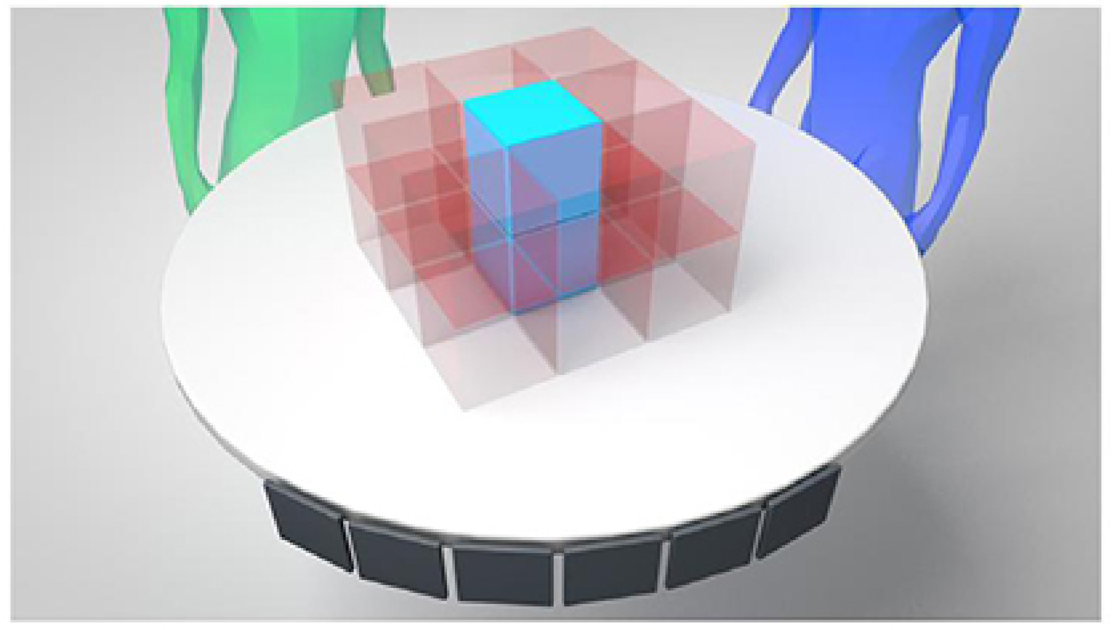


Fig. 5.32: *All layers 50% opacity except blue*

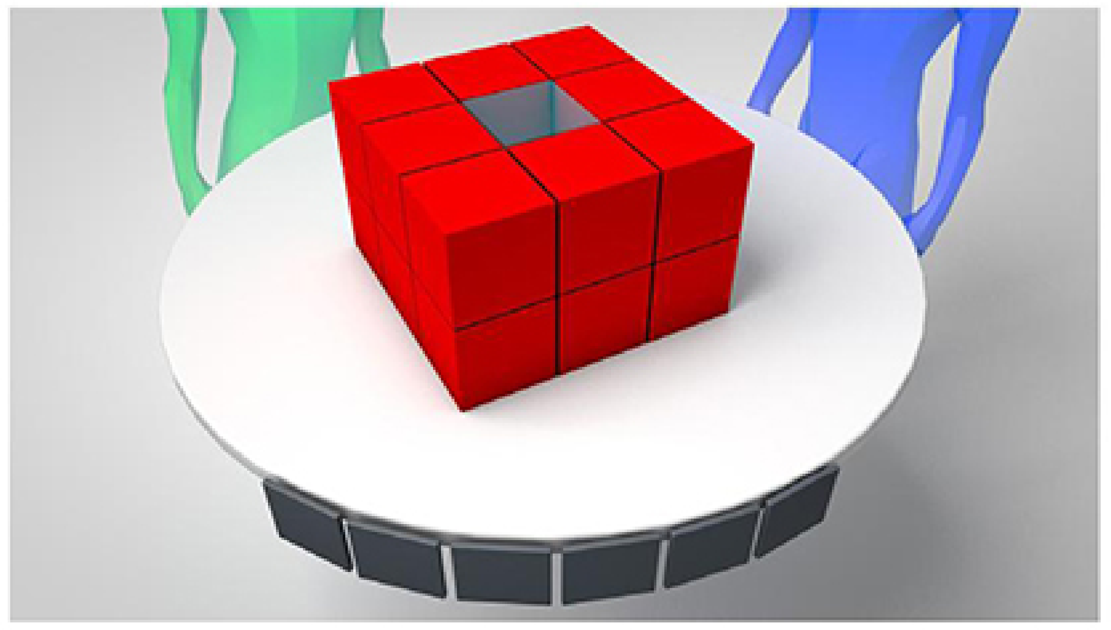
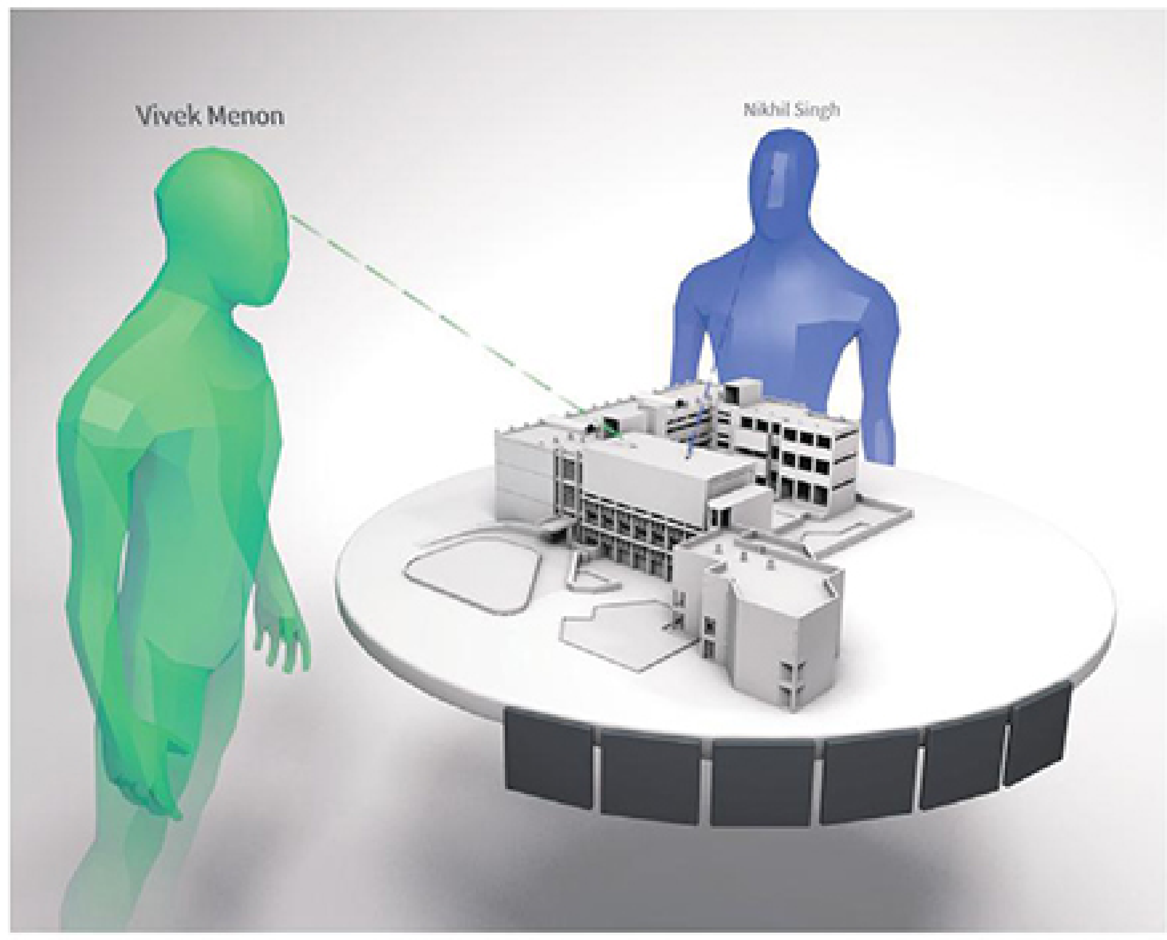


Fig. 5.33: *Blue layer opacity 50%*

3. Scaling the shared 3D Model of the building

Depending on the size of the project the scale of the shared building model may vary. Project with larger sites or built areas can become very small to fit into the bounds of the collaboration station. To view the model in detail, the user can scale up the size of the 3D model within the extents of the collaboration station. The model can be moved and rotated in all three directions to get the desired view.



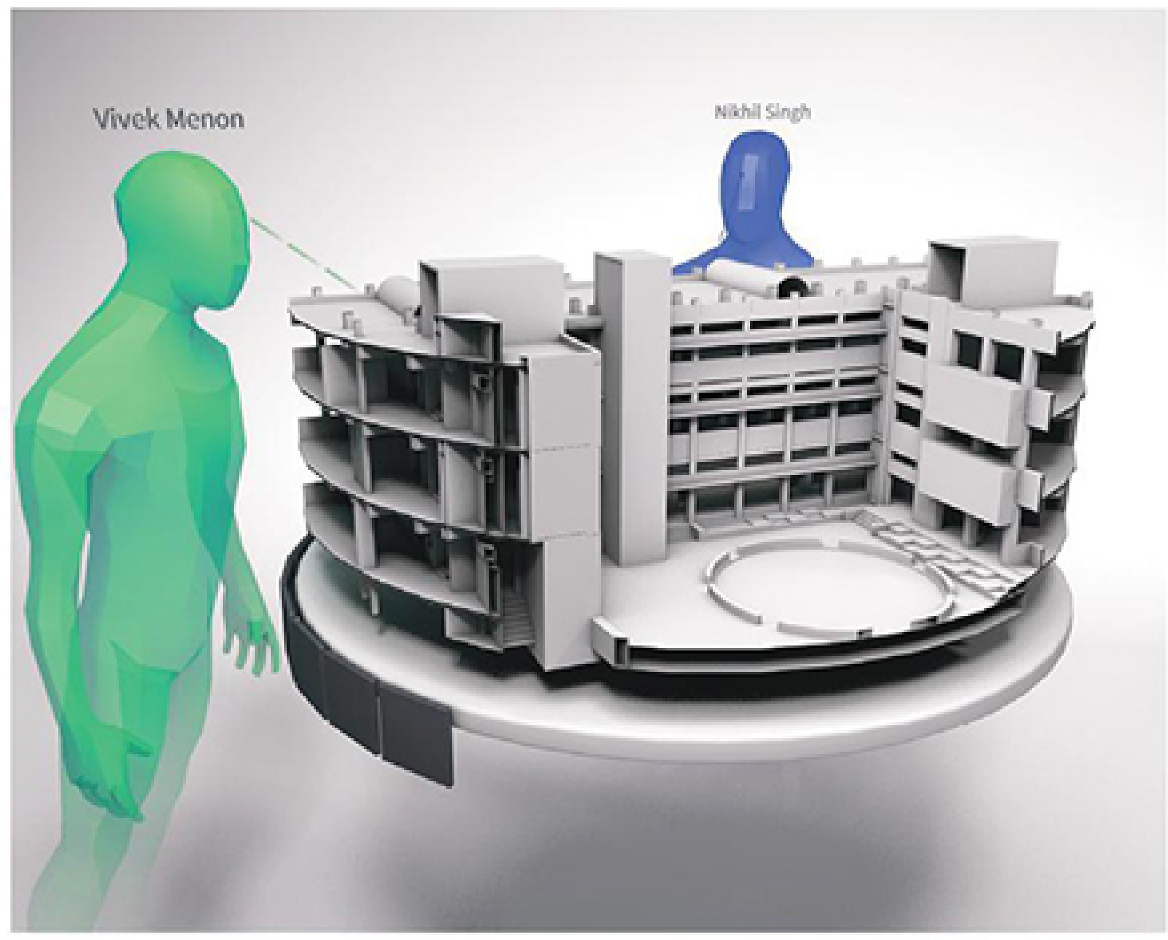
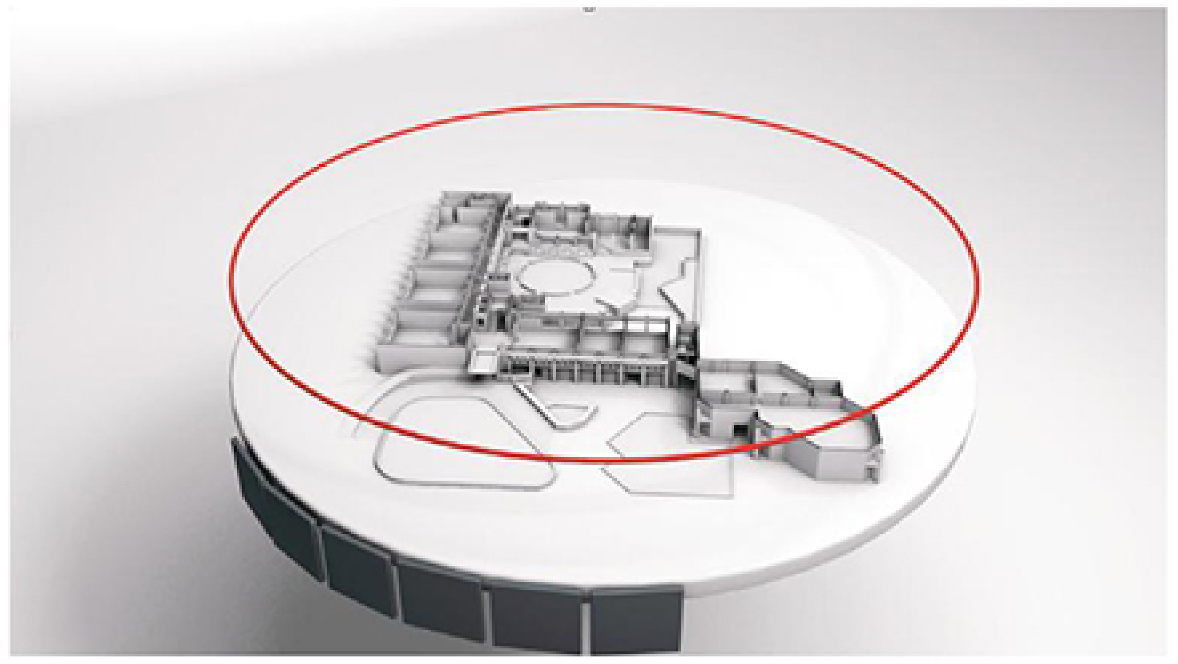


Fig. 5.34: *(Left) 3D model inside the table bounds, Author*

Fig. 5.35: *(Right) 3D model trims with table bounds when scaled up, Author*

4. Adding section/ clipping planes

Section/Clipping planes are of great importance to the AEC industry people to see hidden details and cross sections in the model. The user can add a section/clipping plane which can be moved and rotated freely to get any desired section detail.



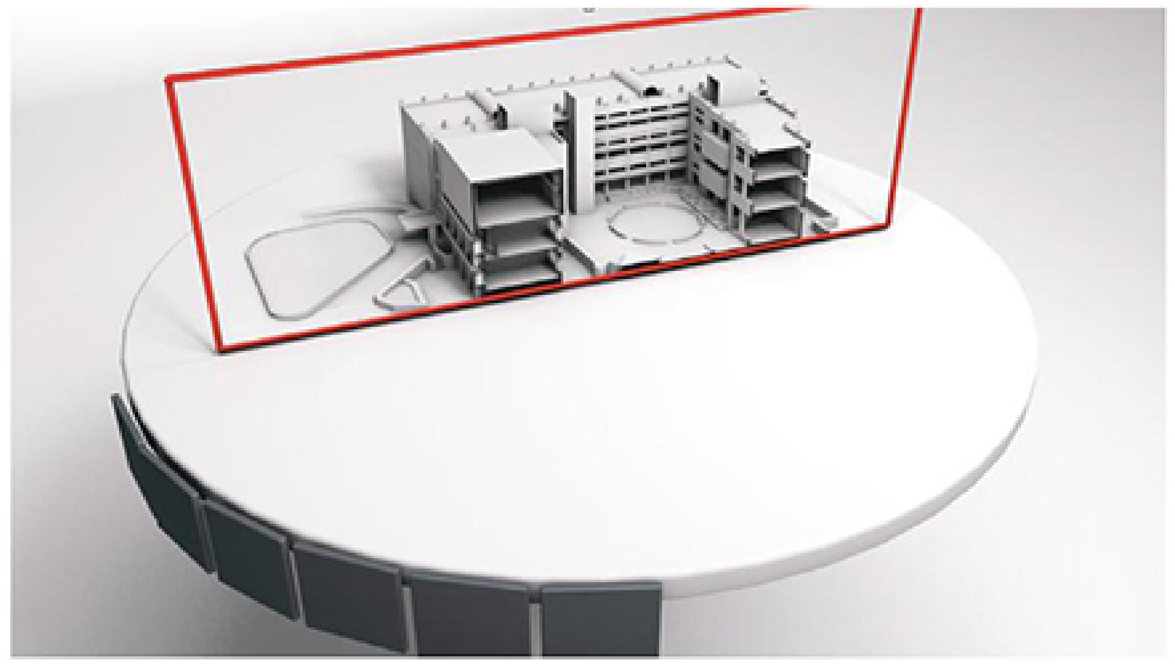


Fig. 5.36: *(Left) horizontal clipping/ section plane*

Fig. 5.37: *(Right) Vertical clipping/ section plane*

Communicative Activities

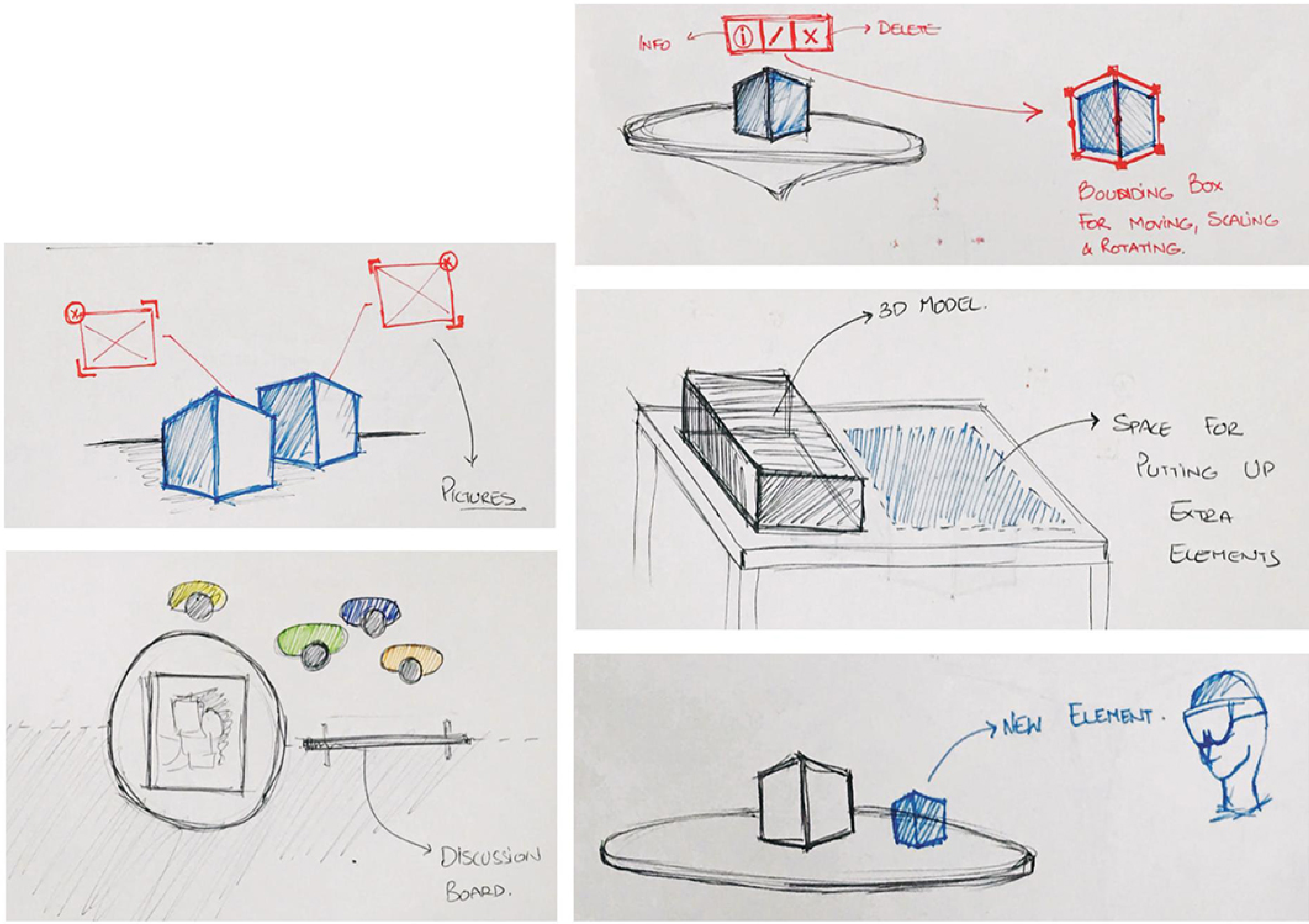


Fig. 5.38: *Different modification interaction explorations, Author*

1. Adding Annotations

The user can add annotations on the shared model which all other collaborators can see. Annotations take input by speech and convert it into text. An annotation can also be added by voice command while gazing at the point where you need to add one. Other collaborators can upvote or downvote a comment for coming at a consensus.

2. Discussion Board

The collaborators can have shared virtual discussion/ pin board where they can pin architectural drawings, pictures or videos for reference and discussions. These resources are of great importance during project meetings.

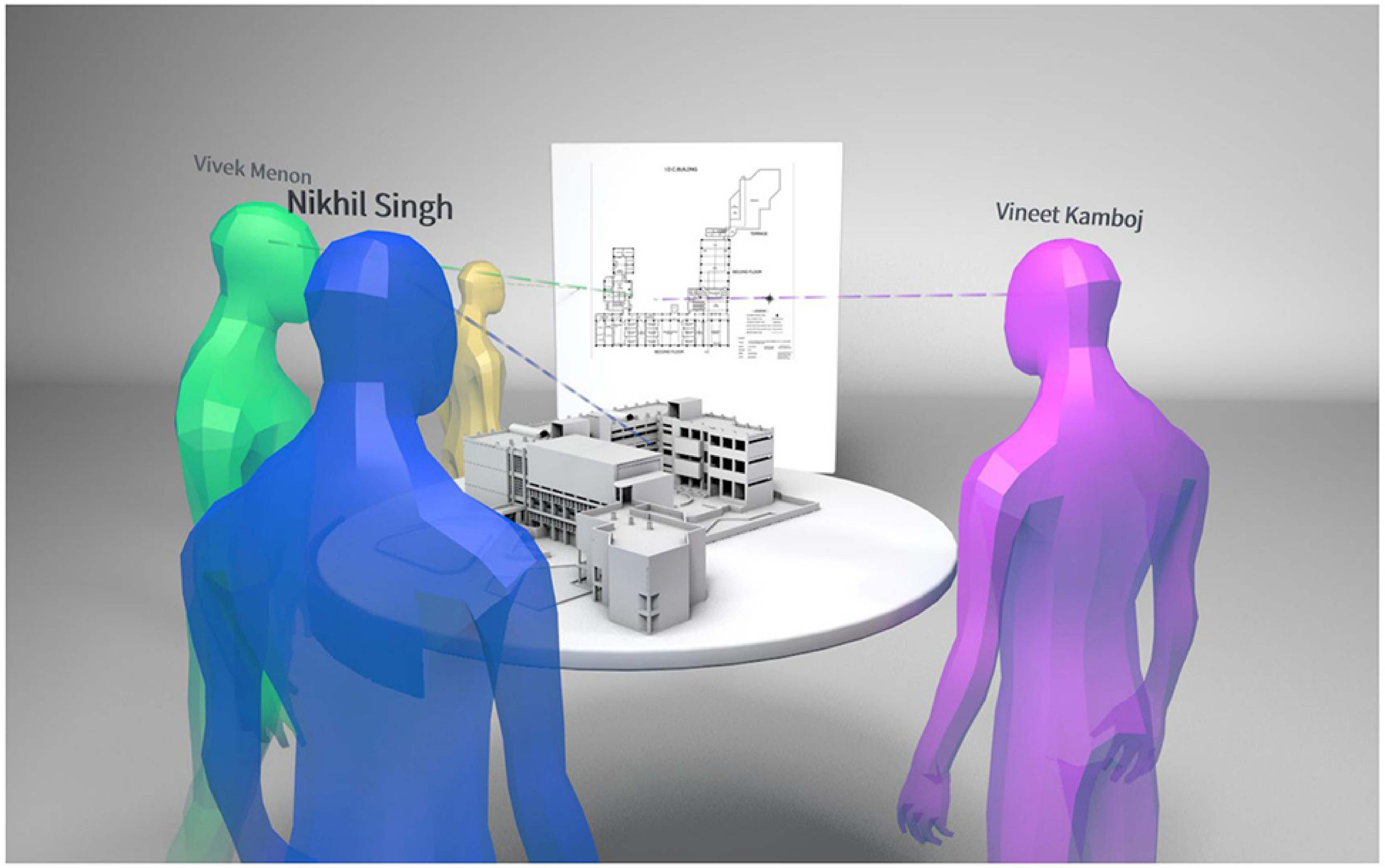


Fig. 5:39: *Collaborators in a session using the discussion board, Author*

3. 3D Draw

Users can draw in 3D to mark things on the model or on the discussion board.

5.8 Design Decisions

This section describes various design decisions taken while designing the interface, interactions, and experience for the collaborative platform.

1. Collaboration Station

The collaboration station is mainly a circular table which the user places in his environment. The Idea is to have collaborators stand around a table and look at the model which is similar to how different participants view physical models in an actual co-located meeting scenario. Since we can not assume the presence of the same table at all the offices, we provided a standard table which the user can place in an open area.

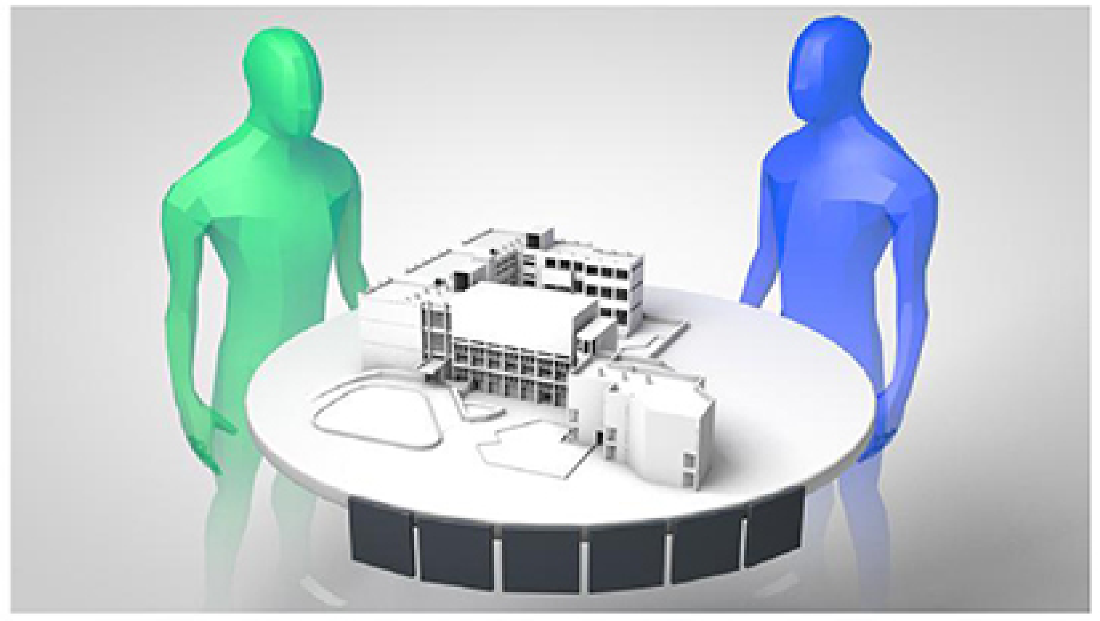


Fig. 5.40: *Circular shaped collaboration station, Author*

Based on a study done by Microsoft which tells about how the movement of the people is restricted or hindered by the shape of the table/platform used in a mixed reality experience. The study shows that a rectangle shaped platform resulted in people not moving around the 3D elements. It happens because when the user due to the immersion in the virtual environment, they start treating the virtual objects as real objects. Walking around a rectangular table is not intuitive nor smooth whereas walking around circular table comes naturally.

2. Main Menu and Submenu

The main menu is where the user initiates all the activities. The primary task was to decide the location of the Menu. The menubar had to be accessible and in the users reach without blocking the view of the shared model or other shared elements. Finally, the menu bar was made sick to the edge of the table. The menu bar revolves around the table edge following the user and facing the user always.

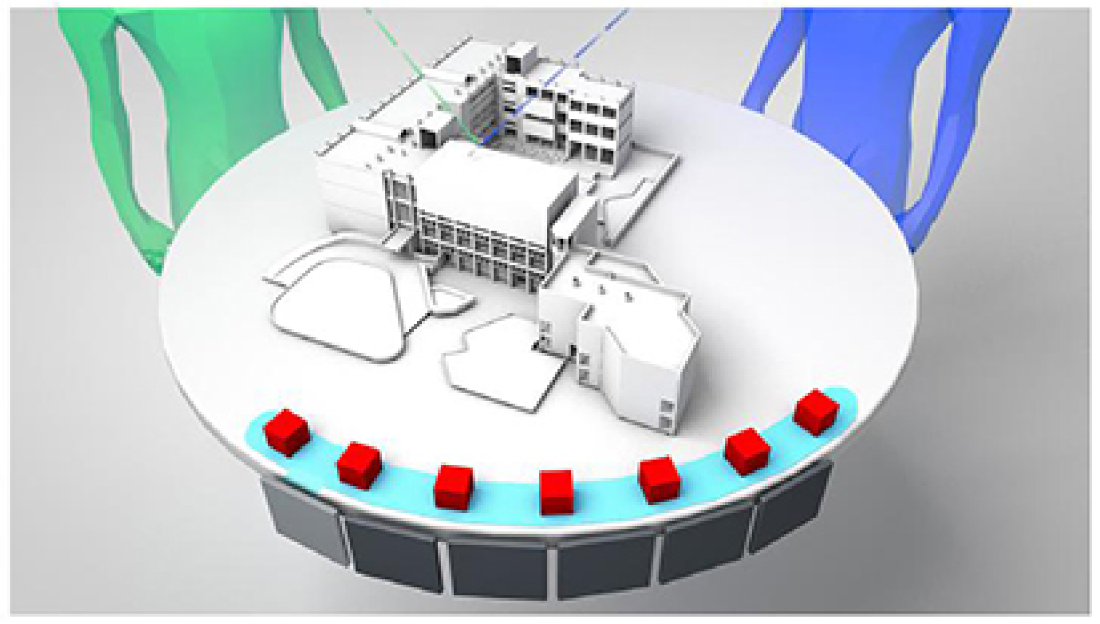


Fig. 5.41: *Blue band maintains the relationship between main menu and submenu, Author*

Since the main menu bar took place on the table edge, the submenu had to come somewhere else. Using the space around for submenu items or the whole menu system would cause the interface to collide with other elements like virtual avatars, 3D model of the structure, etc. To avoid such issues, we divided the table top into two concentric circles. The outer ring hosts the submenu which allows maintaining the relationship between the main menu and the submenu. A colored ring joins the selected item from the main menu to the submenu items in the selected item.

3. Virtual Avatars

In remote collaboration scenarios, the user perceives other collaborators as virtual avatars. A name tag placed around the head of the avatars makes them identifiable. Displaying the name wasn't enough, so each avatar gets a unique color which allows the user to differentiate between the avatars and recognize them readily. A tooltip displaying the actions of the user (virtual avatars) is present around the head.

In a real-world scenario, we use our voice, hands and other unintentional expressions while communicating with others. We generally point at things using our hands while talking. A virtual avatar is just a visual representation of another person which cannot move its hands nor have facial expressions. Users connected through VoIP (Voice over internet protocol) can talk to each other using spatial sound. To allow the user to communicate effectively, we substituted the unintentional expressions with a line coming out from the users head which shows the gaze location of the user.

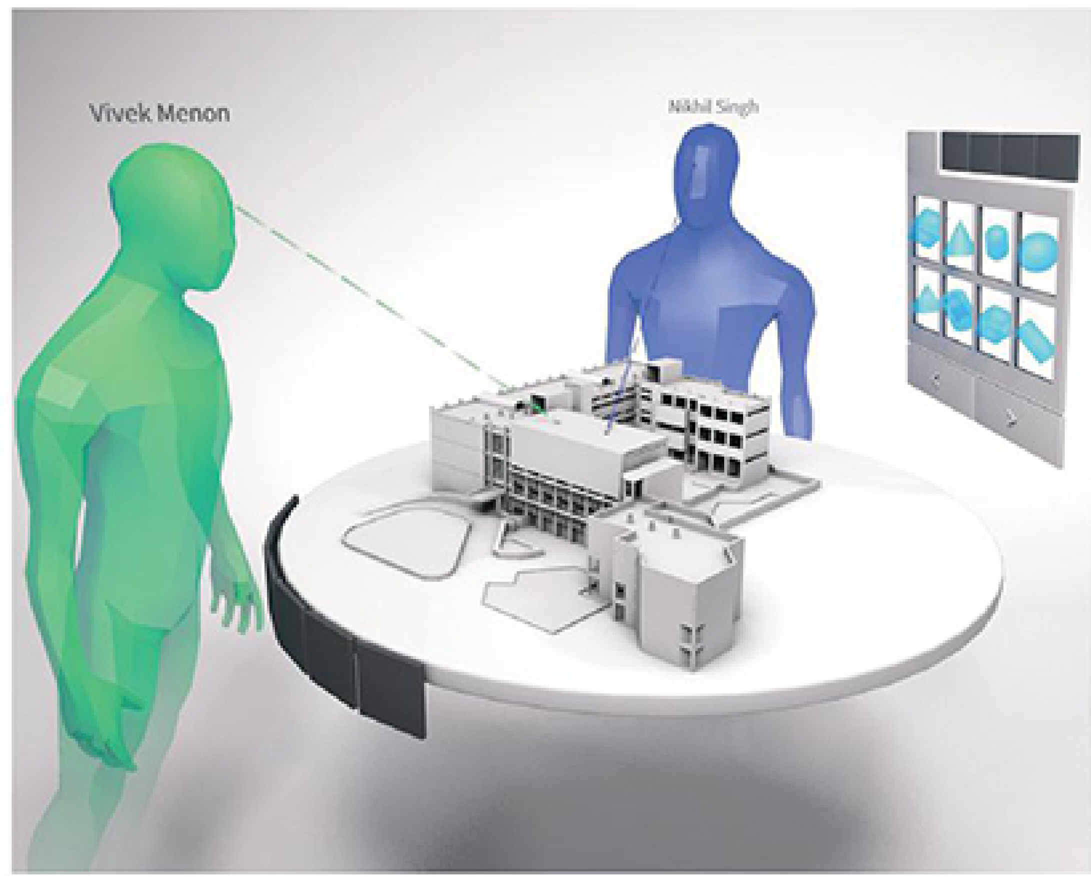


Fig. 5.42: *Gaze sharing helps to know where the other user is looking, Author*

4. Awareness

While designing CSCW/ Groupware systems, one of the fundamental points is to make sure that the user is aware of the actions and activities of all other collaborators. In our case, if a collaborator selects an element for moving it, all the other collaborators should get to know the following things;

- Which element is selected
- Who made the selection
- What modification is occurring

• Selection Awareness

When a user selects an element, the color of the chosen element changes to the color of the virtual avatar of the user who made the selection. E.g., If a component turns red, the user would know the collaborator in red made the selection.

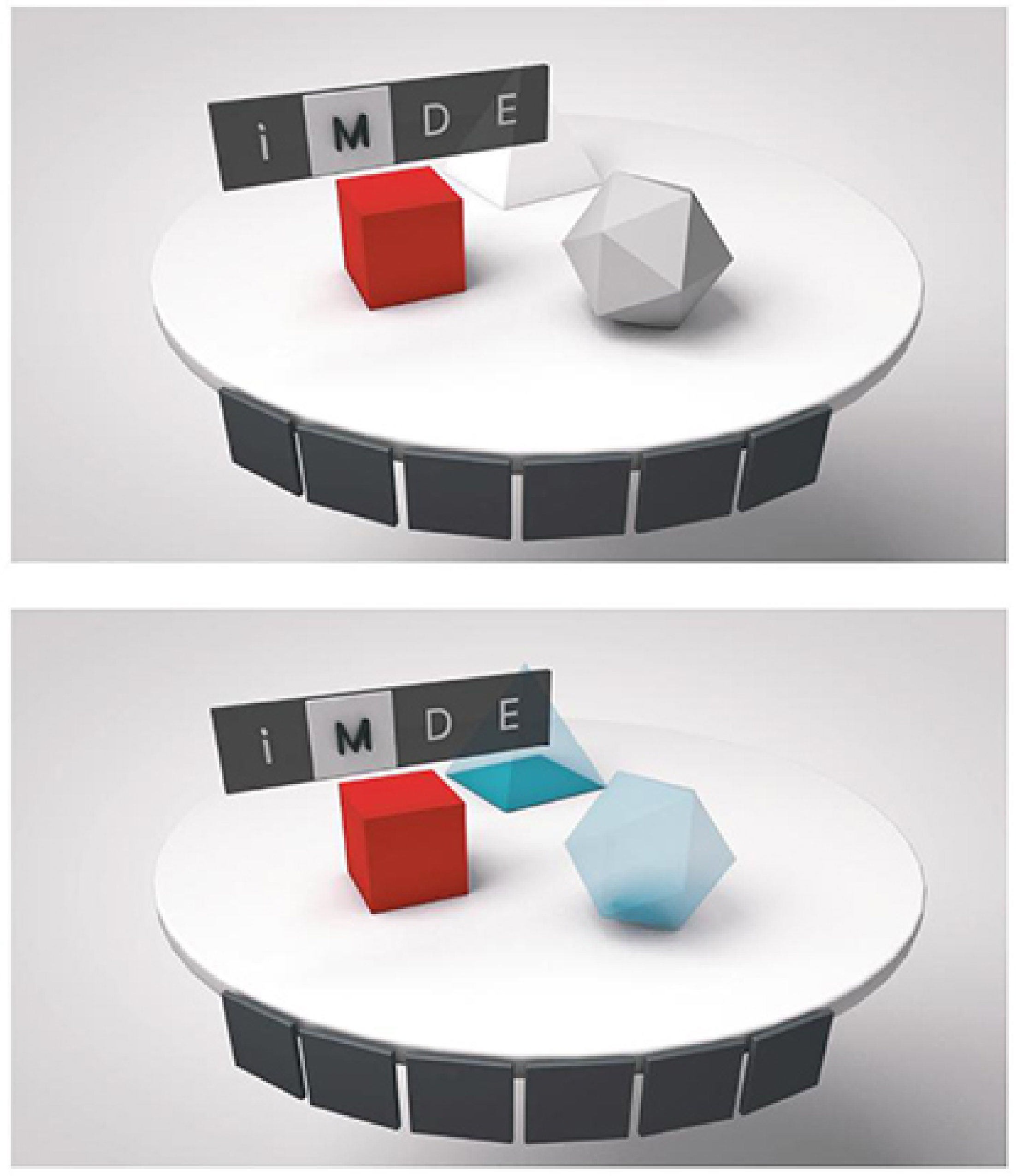


Fig. 5.43: *Selection awareness concepts, element menu, Author*

• Modification Awareness
If a collaborator moves, scales or rotates the element, all other collaborators can see the change in state of the selected object in real-time.

• Addition of an element
When a collaborator (e.g., red color avatar) adds an object, the newly added item appears as red to all the collaborators for a few seconds. The color informs the collaborators about who added the element.

• Deletion of element
When a collaborator deletes an object, a ghost of the object is left behind for a few seconds. The ghost object is of the same color as the virtual avatar of the user who deleted the object which informs other users of the deletion.

5. Spatial Audio
In a remote collaboration scenario, all the collaborators can talk to each other over VoIP. When there are more than three collaborators, the user might get confused about who is speaking among the virtual avatars at a given instance. We made use of spatial audio to resolve this issue. With the help of spatial audio, the user can get to know from which virtual avatar the sound is coming.

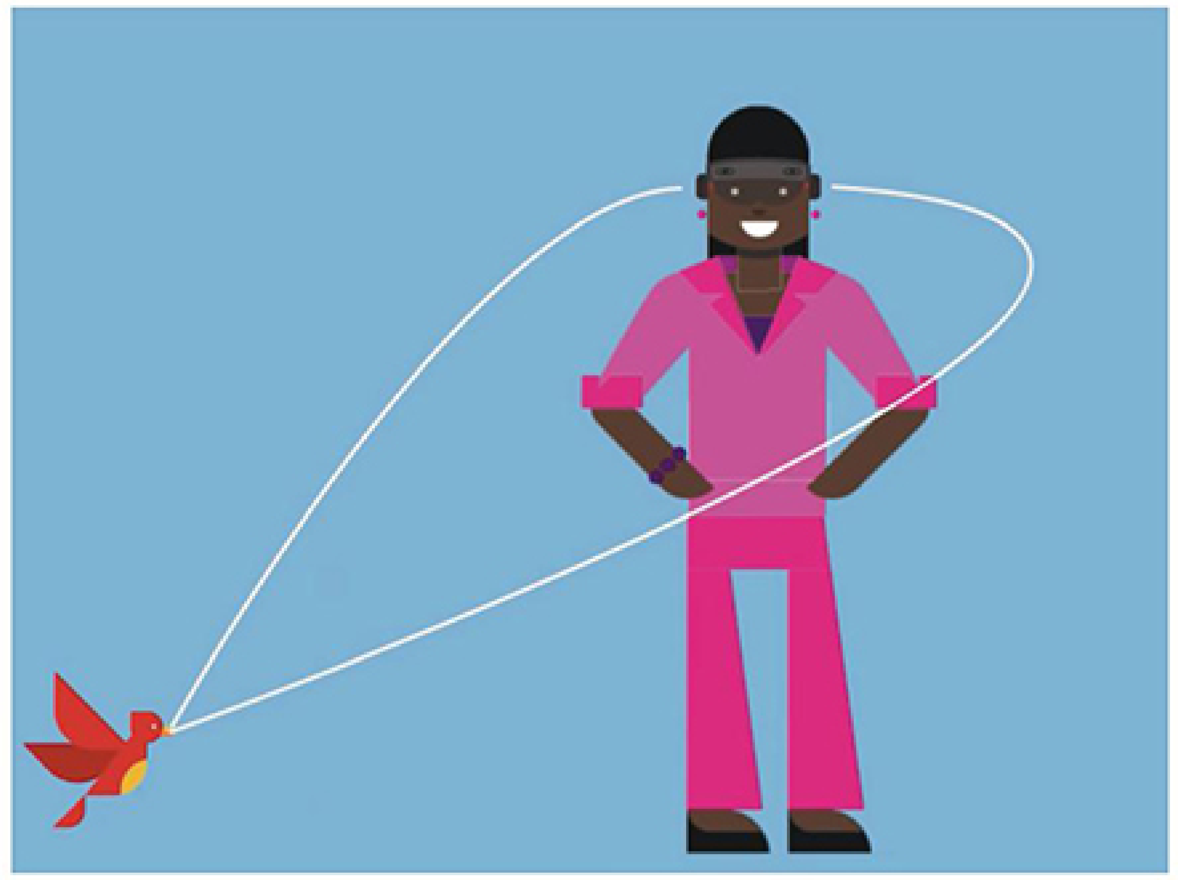


Fig. 5.44: *Spatial sound for avatar identification, Microsoft*

5.9 Information Architecture

Fig. 5.45 shows the information architecture of the HoloLens collaboration platform. The architecture has three major components: Collaboration Station, Main Menu and 3D model. The user can access all the major components from the main menu. The architecture also show the menu of other items like elements, discussion board, section plane, etc.

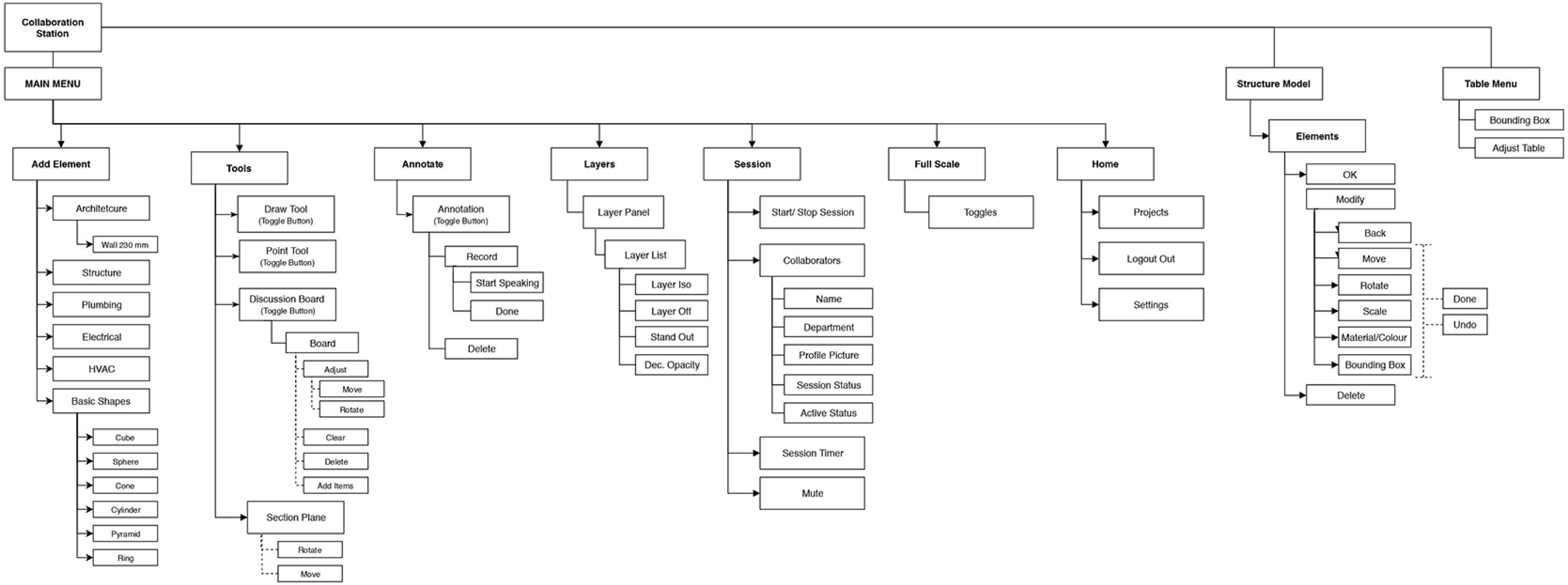
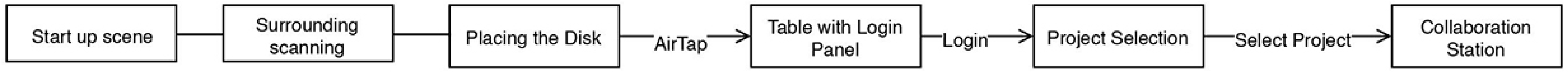


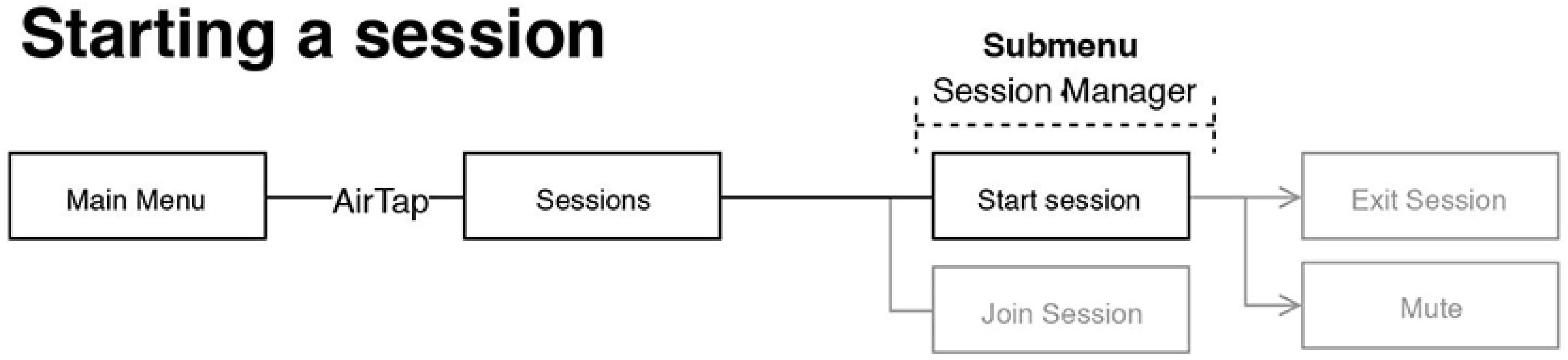
Fig. 5.45: *Hololens application information architecture*

5.10 Activity Flowcharts

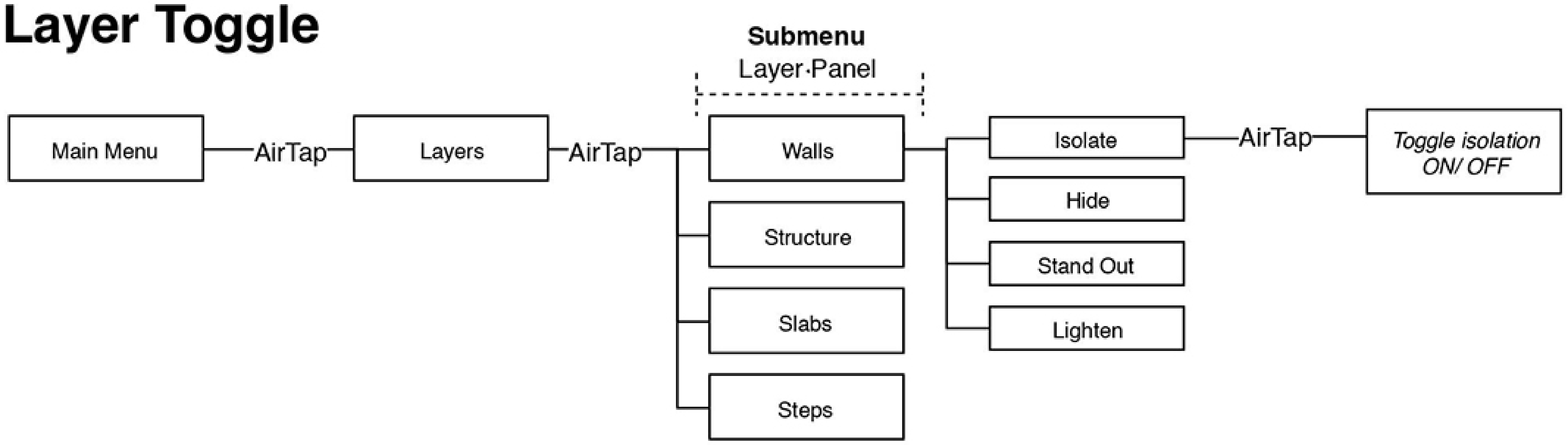
App Flow



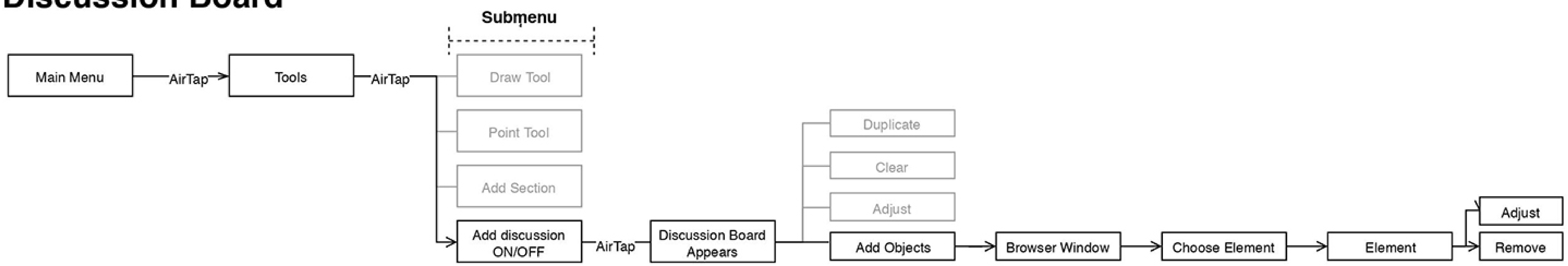
Starting a session



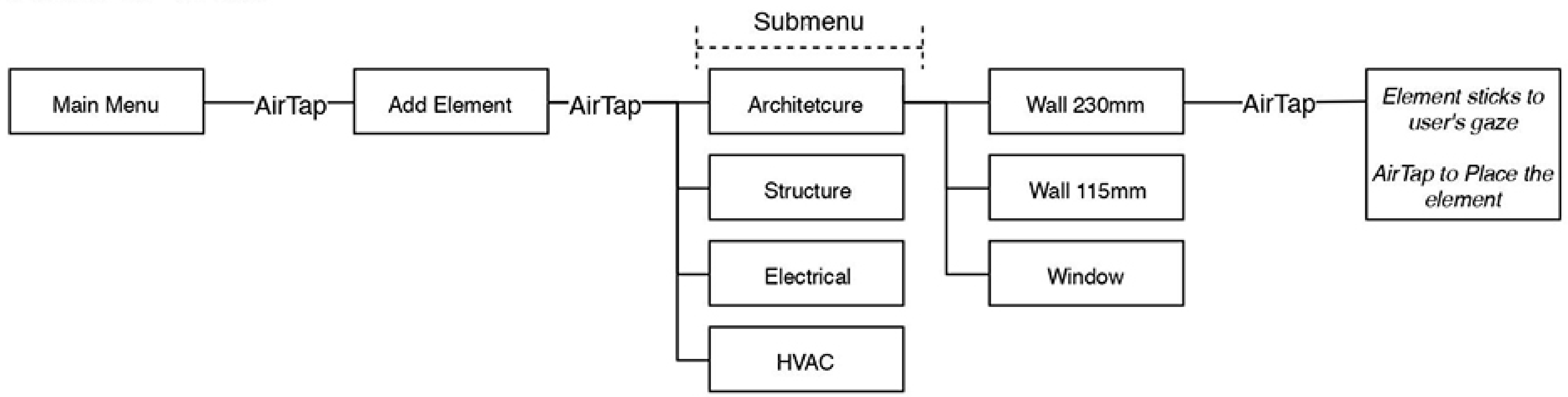
Layer Toggle



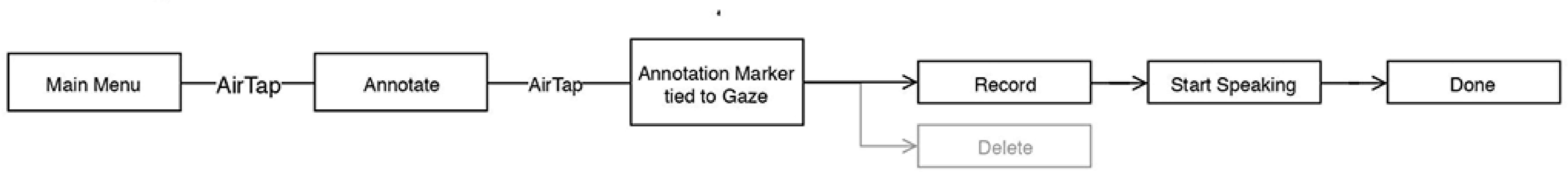
Discussion Board



Add a Wall



Adding Annotations



5.11 Social Aspects

Referring back to the five classifications given by Koch et al. We define those classifications as per our context.

Co-existence
Co-existence is being aware of the presence of each other and each other's activities. In the case of local collaboration, the collaborators are in the same space and can see each other and their actions.

In the case of remote collaboration, we can augment the presence of the remote collaborator using a virtual 3D avatar of each collaborator. The avatar includes the name and role of the collaborator. When there are more than two virtual avatars, color codes provide a distinction between different participants.

To enhance the co-existence, gaze-tracking is used so that collaborators can see each other point of focus to know where the other person is looking.

Communication
Communication allows the exchange of information between the collaborators and is critical in collaborative working. Communication mechanism should support synchronous as well as asynchronous communications. Synchronous systems include live chats, audio/video calls, and asynchronous systems include emails, etc.
In local collaboration, there is no requirement of synchronous communication as the collaborators are in the same space and can see and hear other collaborators. Voice+textual annotations allow asynchronous communication between all the collaborators. VoIP calling enables the users to communicate synchronously in remote collaboration scenarios. Annotations can work in remote collaboration scenarios as well.

Coordination
Coordination is the act of managing interdependencies between the activities performed to achieve a goal.

In our context, each actor works on a separate layer of the model without affecting other layers (Model Element Authority). So, there are no interdependencies between the activities performed by the actors. The change made in one layer needs a consensus of other collaborators.

For better coordination, we also propose to store a log of changes made by the collaborators which are accessible to all the participants.

Consensus
The consensus is an agreement of all the collaborators over an action or an activity. For, e.g., a change made on a column layer in the structural layer may require an opinion of other collaborators as it could require a change in different layers.

Other participants can give their consensus by marking concerned collaborators in an annotation which can be approved to validate the change.

Collaboration
Collaboration is the real act of working together. In our context the actors are working on a shared resource: a 3D model of the structure. Any manipulation in the shared resource counts as a collaborative activity.

For collaboration to happen, we allow the participants to add, delete or modify the elements of the shared resource (3D Model). Depending on the Model Element Authority on can add, remove or edit the elements (walls, columns, beams, ducts, etc.) in the shared 3D model.

5.12 Scenario

The following section presents a scenario where 3 collaborators use the collaboration platform for designing a space design concept. All the collaborators are located at geographically dispersed locations.

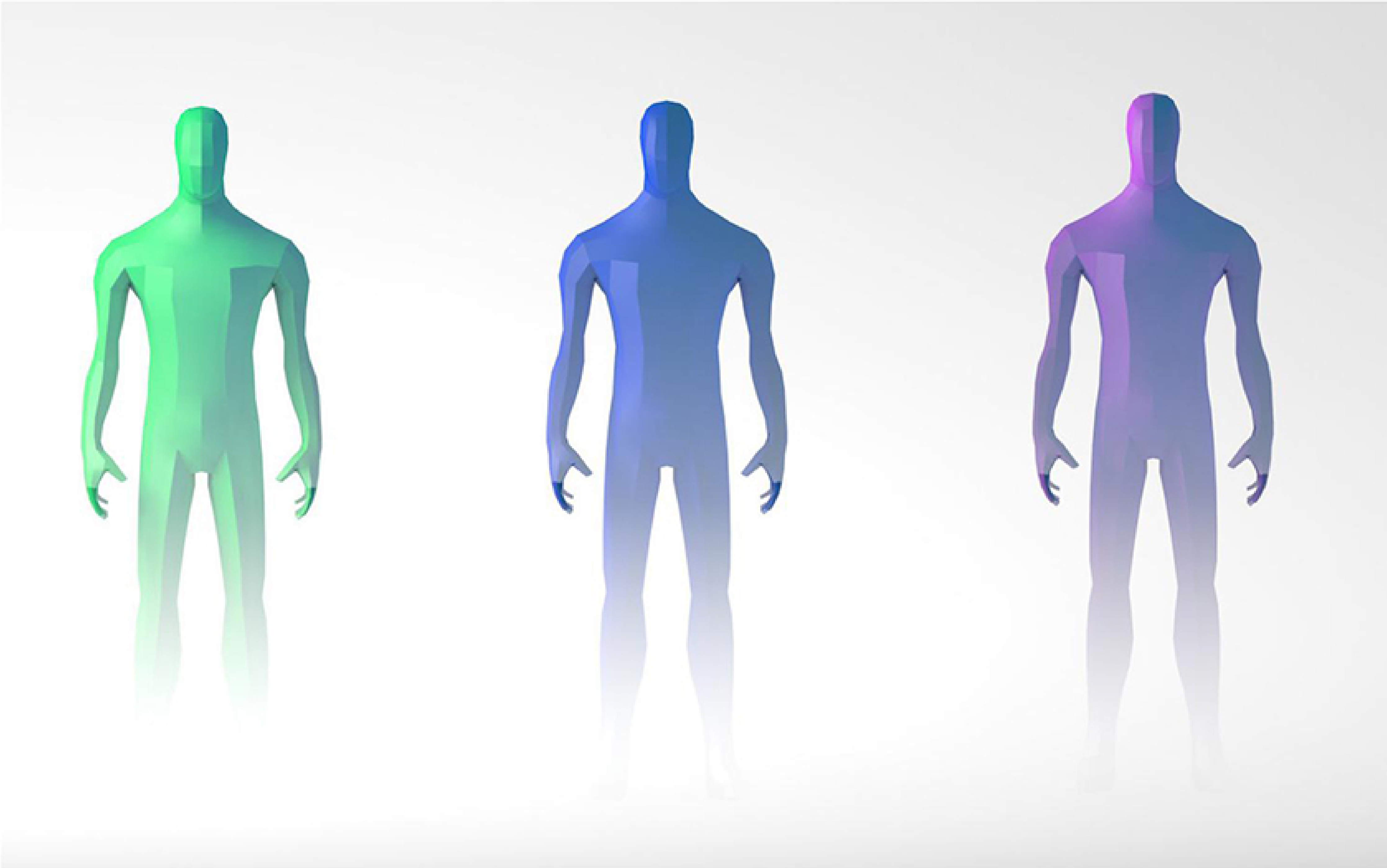


Fig. 5.46: *An architect, HVAC consultant and a structural engineer are remotely located but they want to quickly brainstorm on a concept for space design for a pitch.*

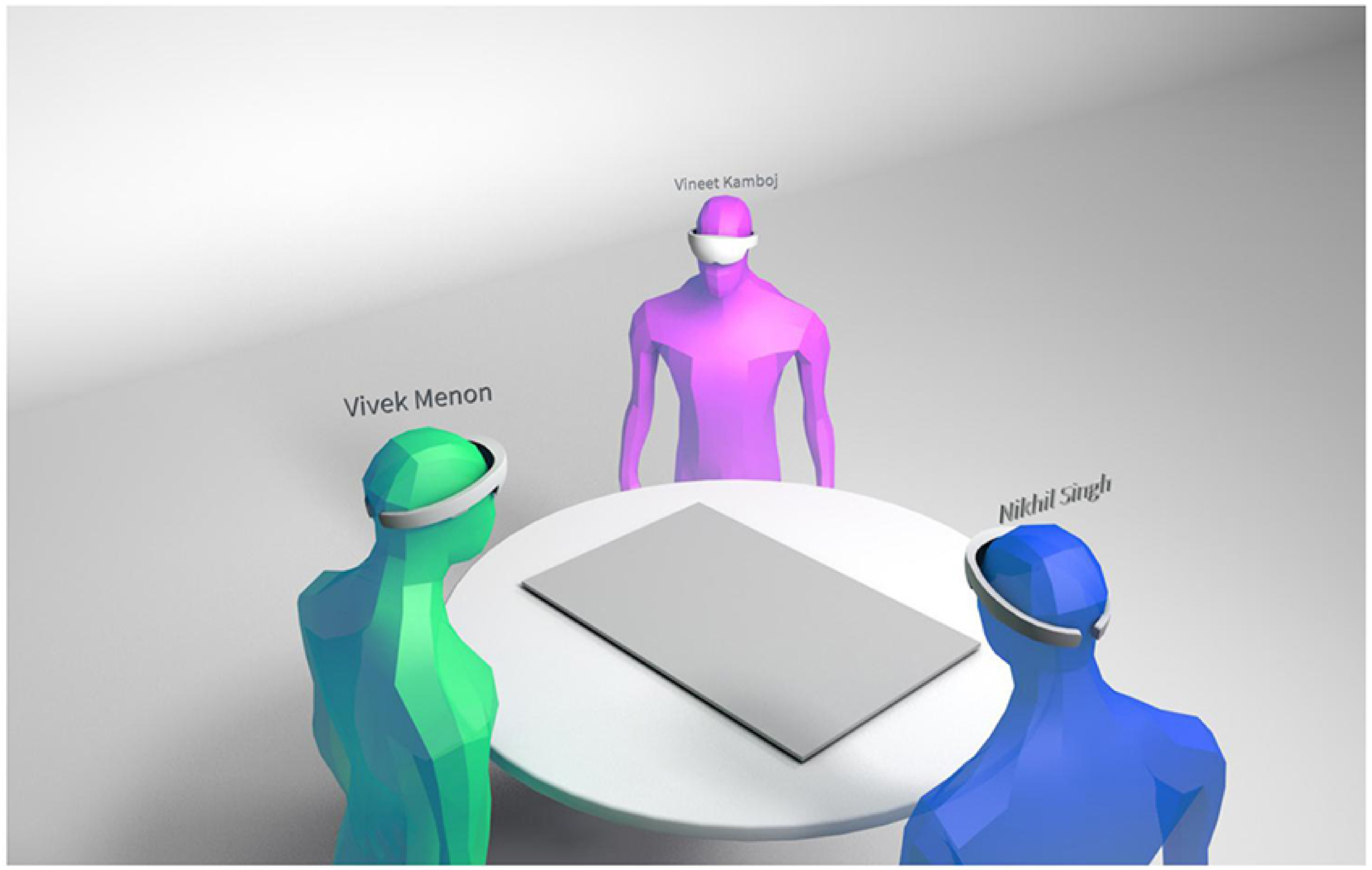


Fig. 5.47: *The architect starts a session on the collaborative platform. Other collaborator join the session shortly. They can now see each other as virtual avatars.*

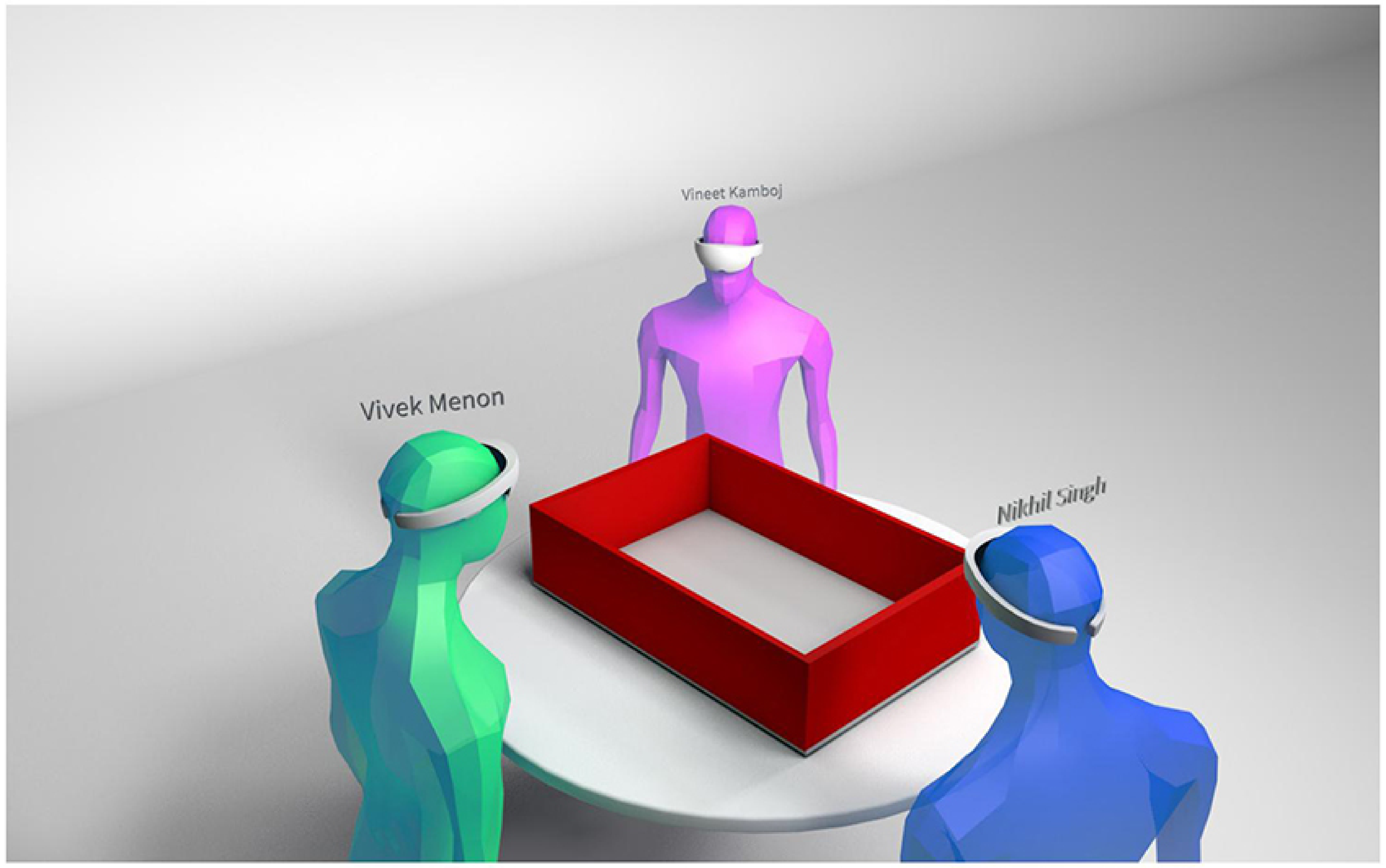


Fig. 5.48: *The architects adds and places a wall element on the table.*

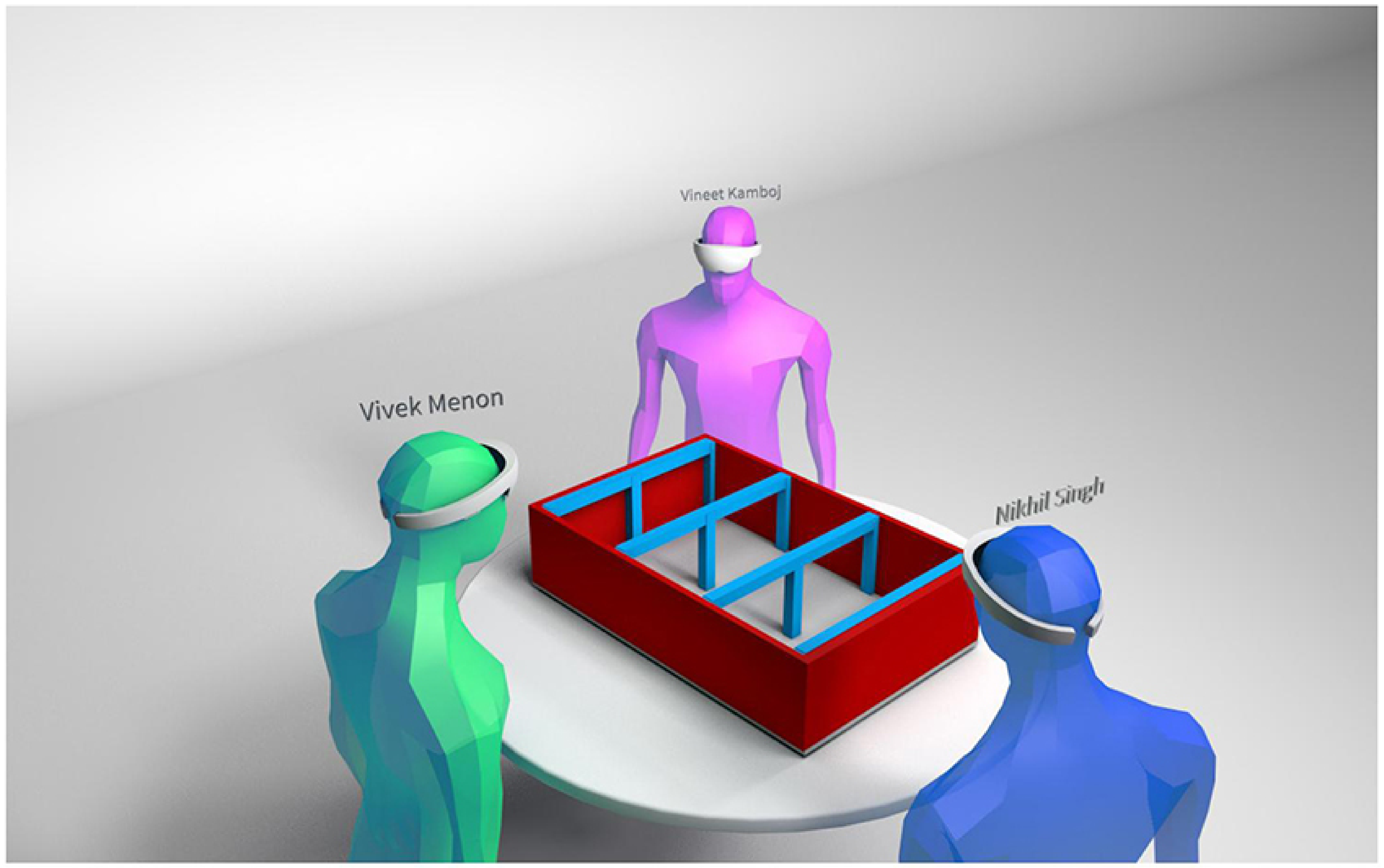


Fig. 5.49: *Structural engineer starts adding beams and columns to give structural framework.`*

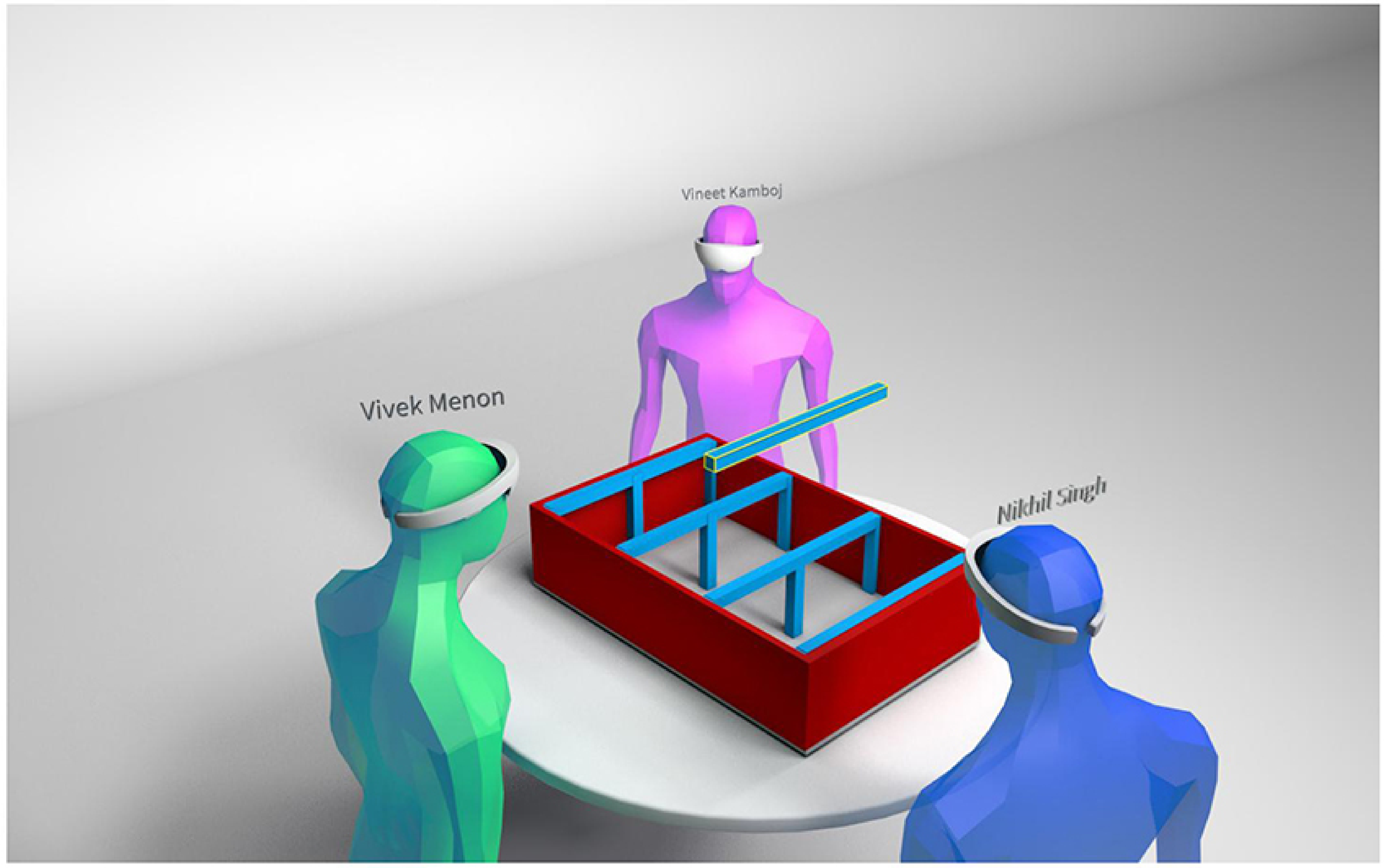


Fig. 5.50: *The figure shows structural engineer (in blue) adding a beam element on the table.*

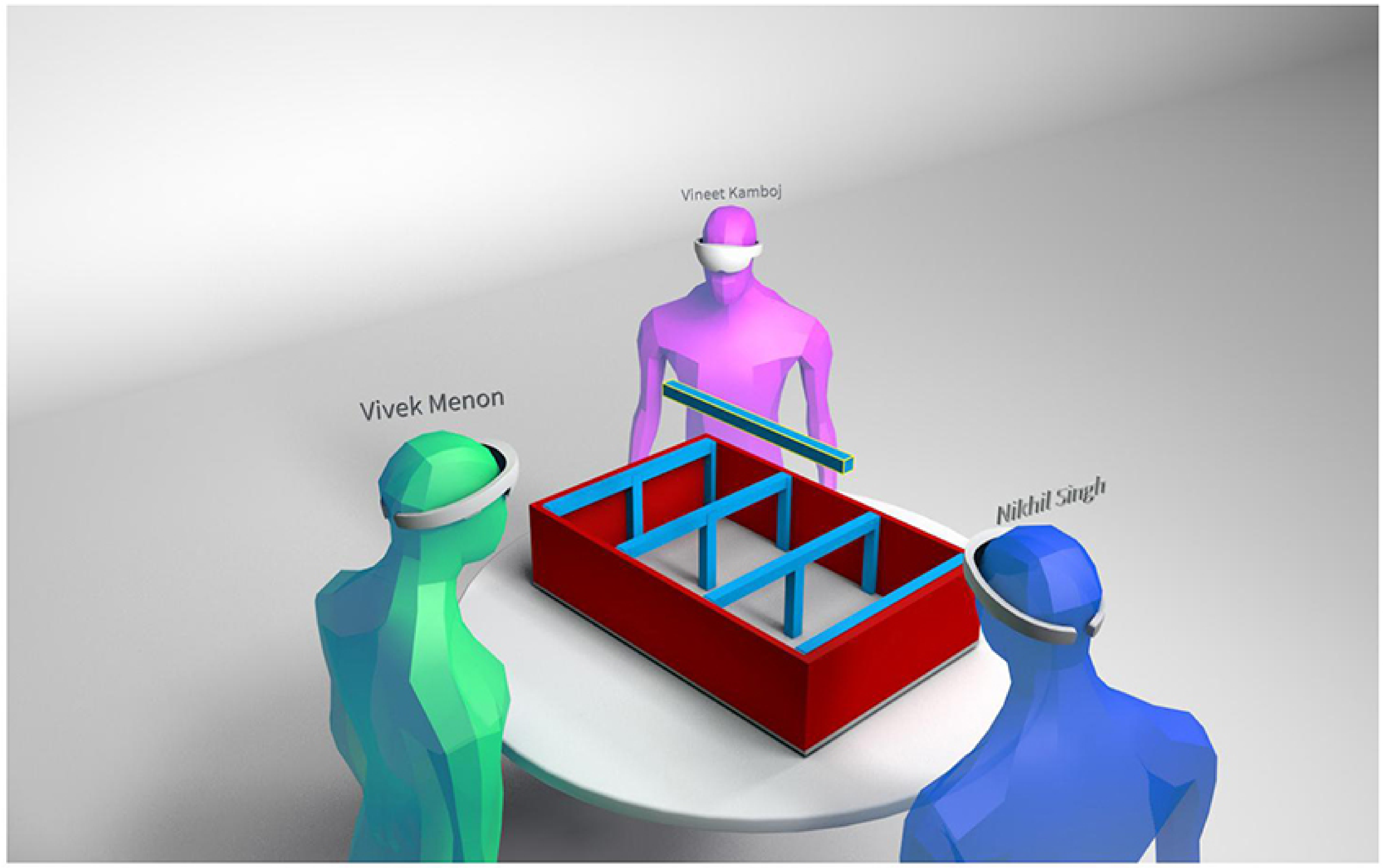


Fig. 5.51: *The blue avatar rotates the element to align it to desired position.*

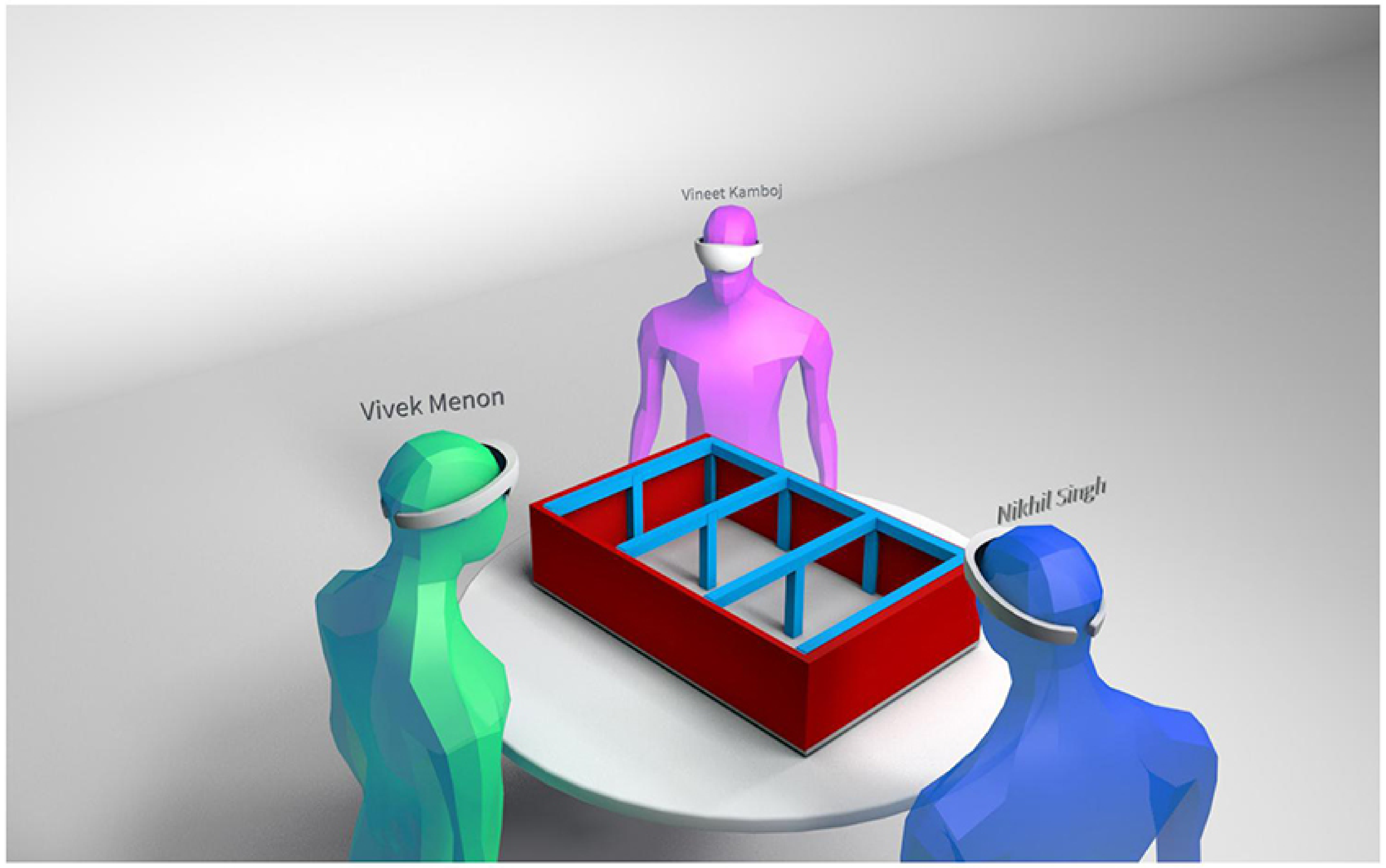


Fig. 5.52: *All three collaborators are working towards the same goal.*

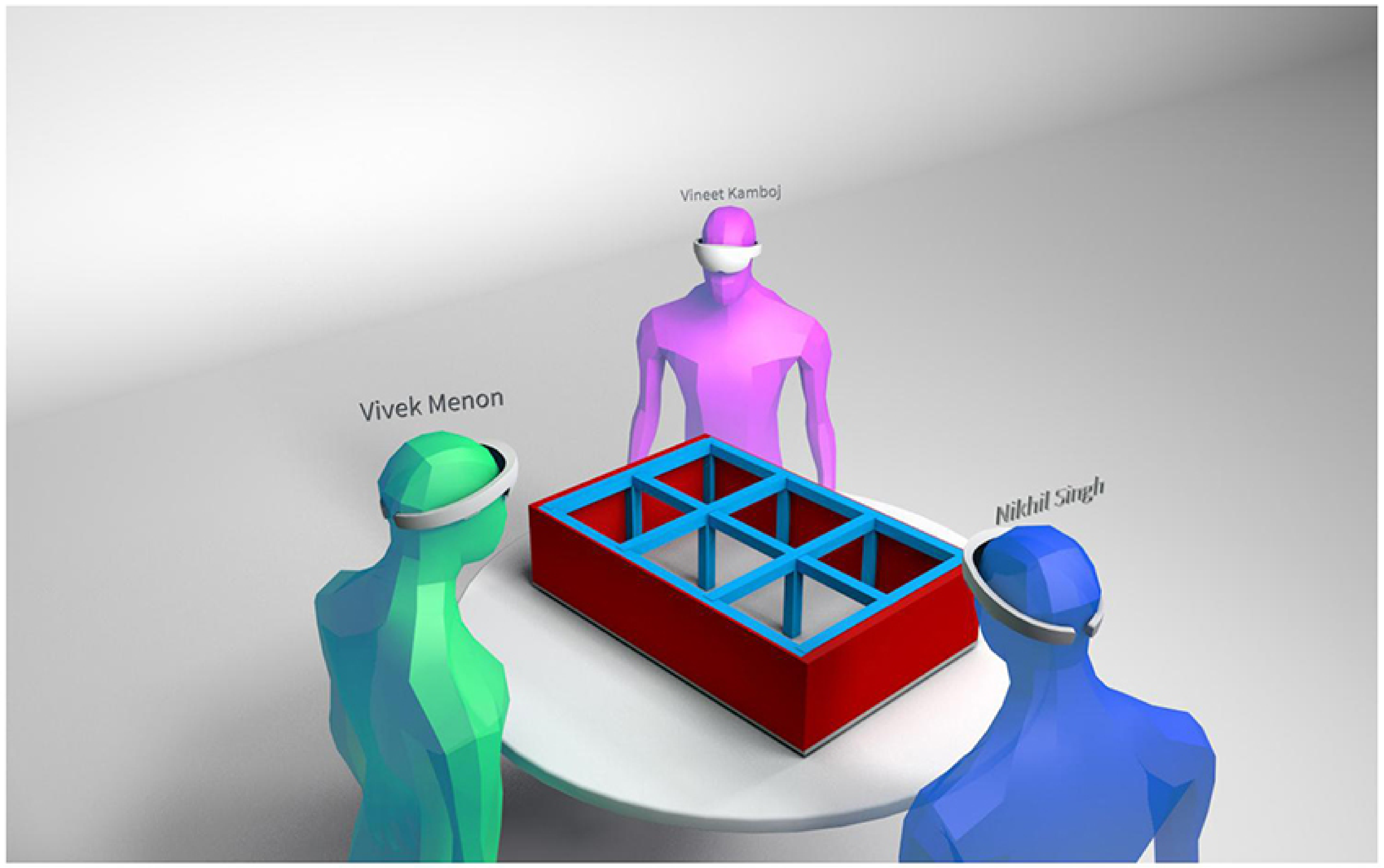


Fig. 5.53: *Once the basic frame of the structure is complete, the architect asks HVAC consultant to add ducting to the model.*

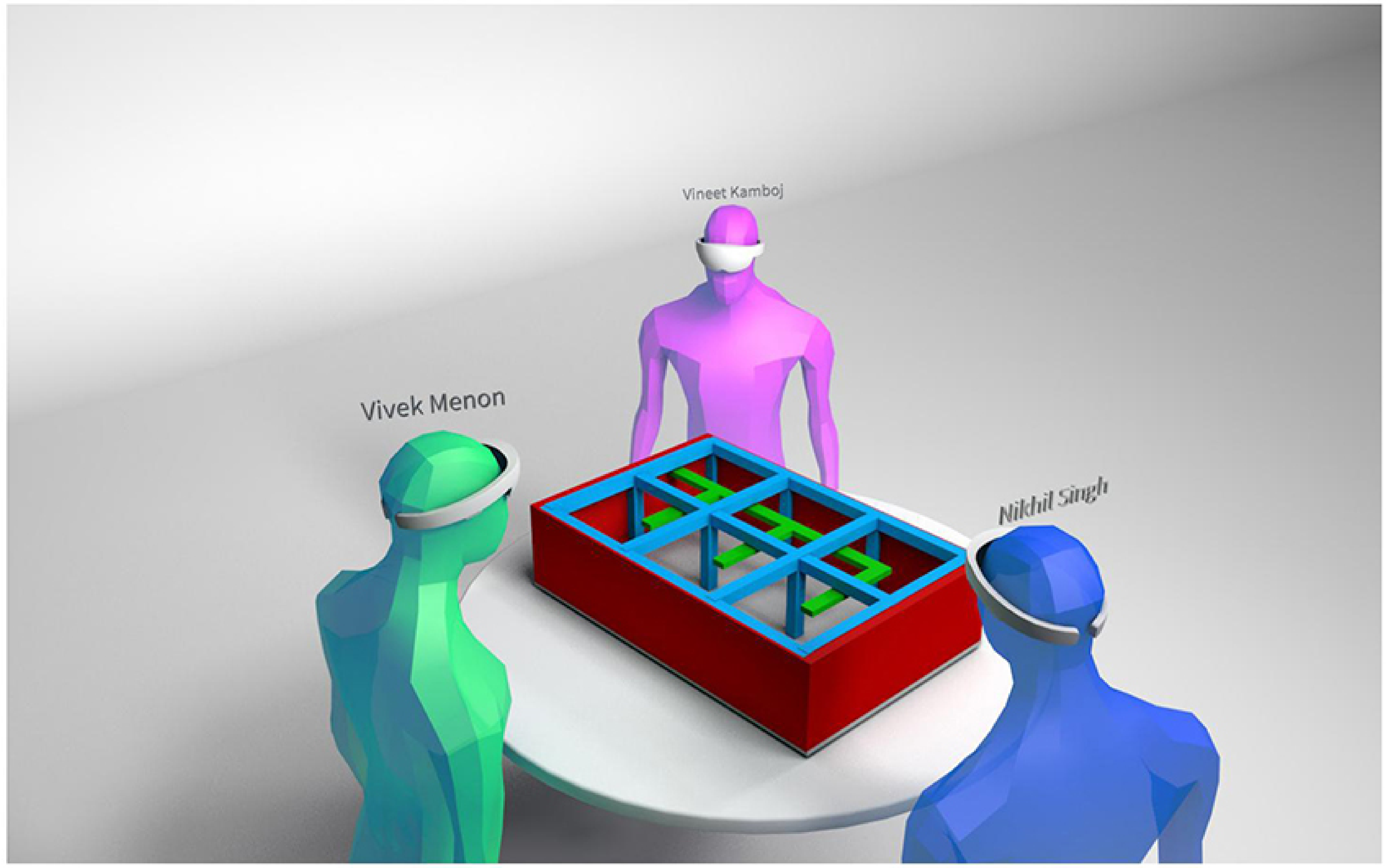


Fig. 5.54: *HVAC consultant (in pink) adds the ducting element as per the beam and column placement.*

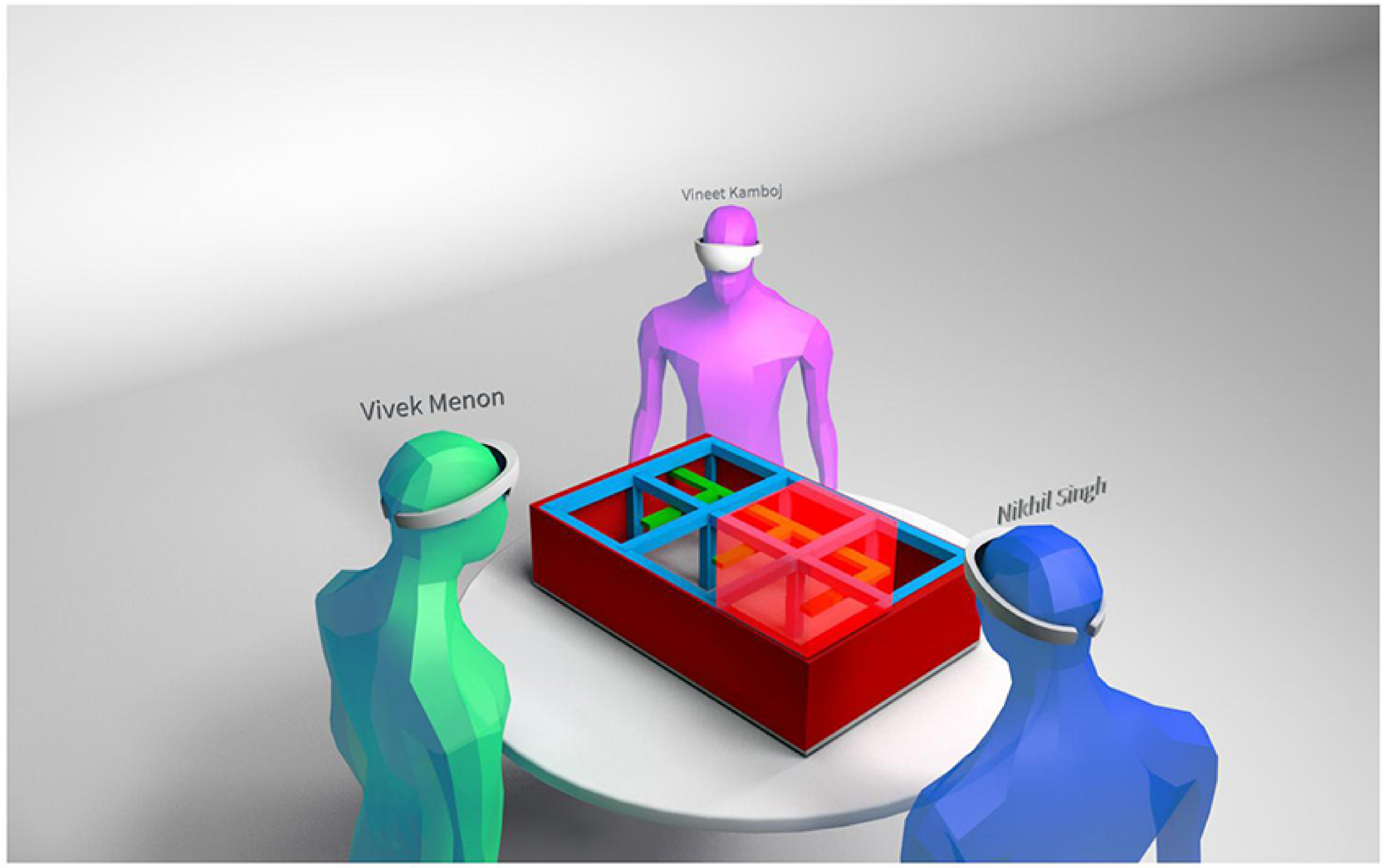


Fig. 5.55: *The architect creates a HVAC room to indicate the outlet for the ducts*

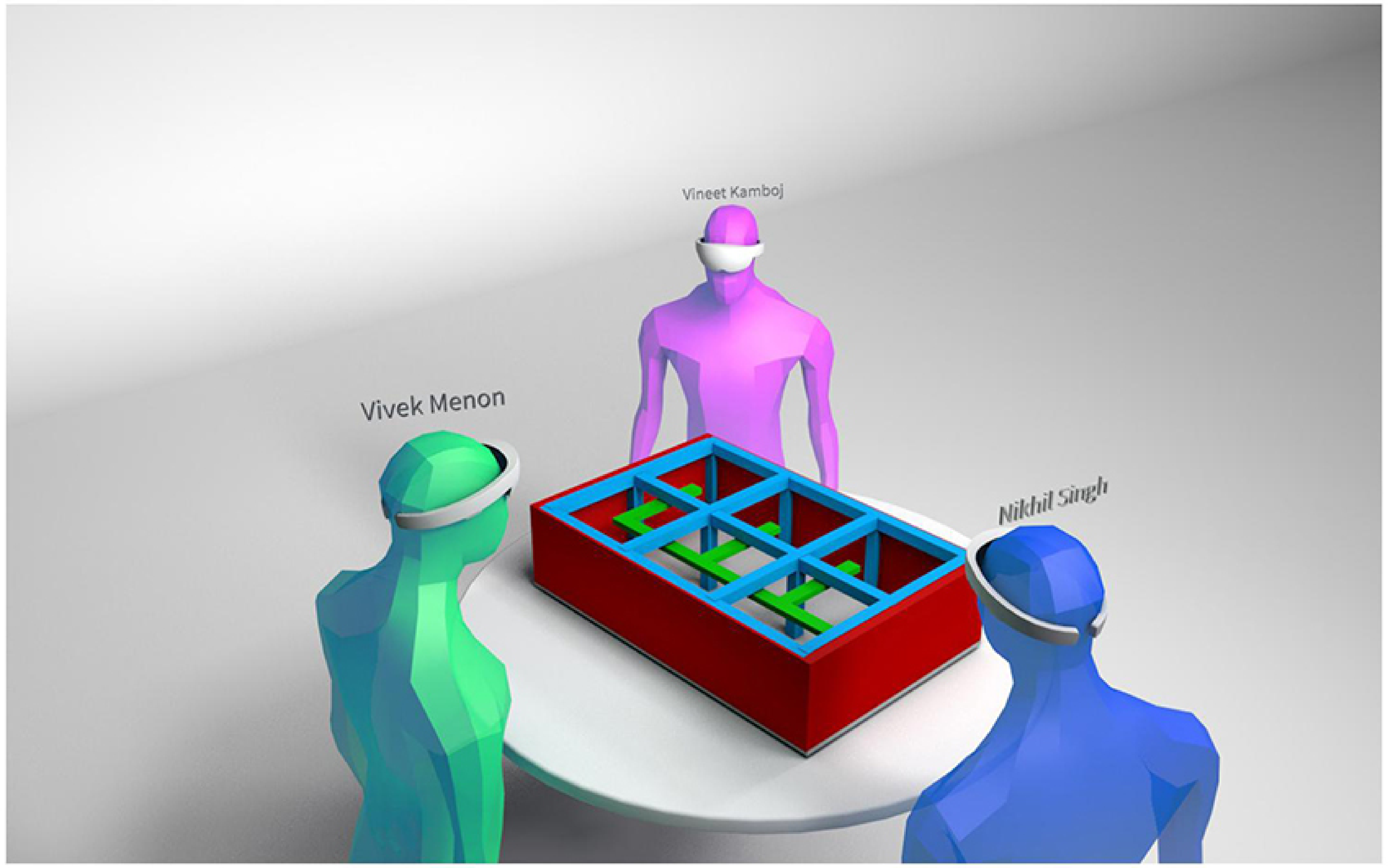


Fig. 5.56: *HVAC consultant changes the rotation of the ducts as desired by the architect (in green)*

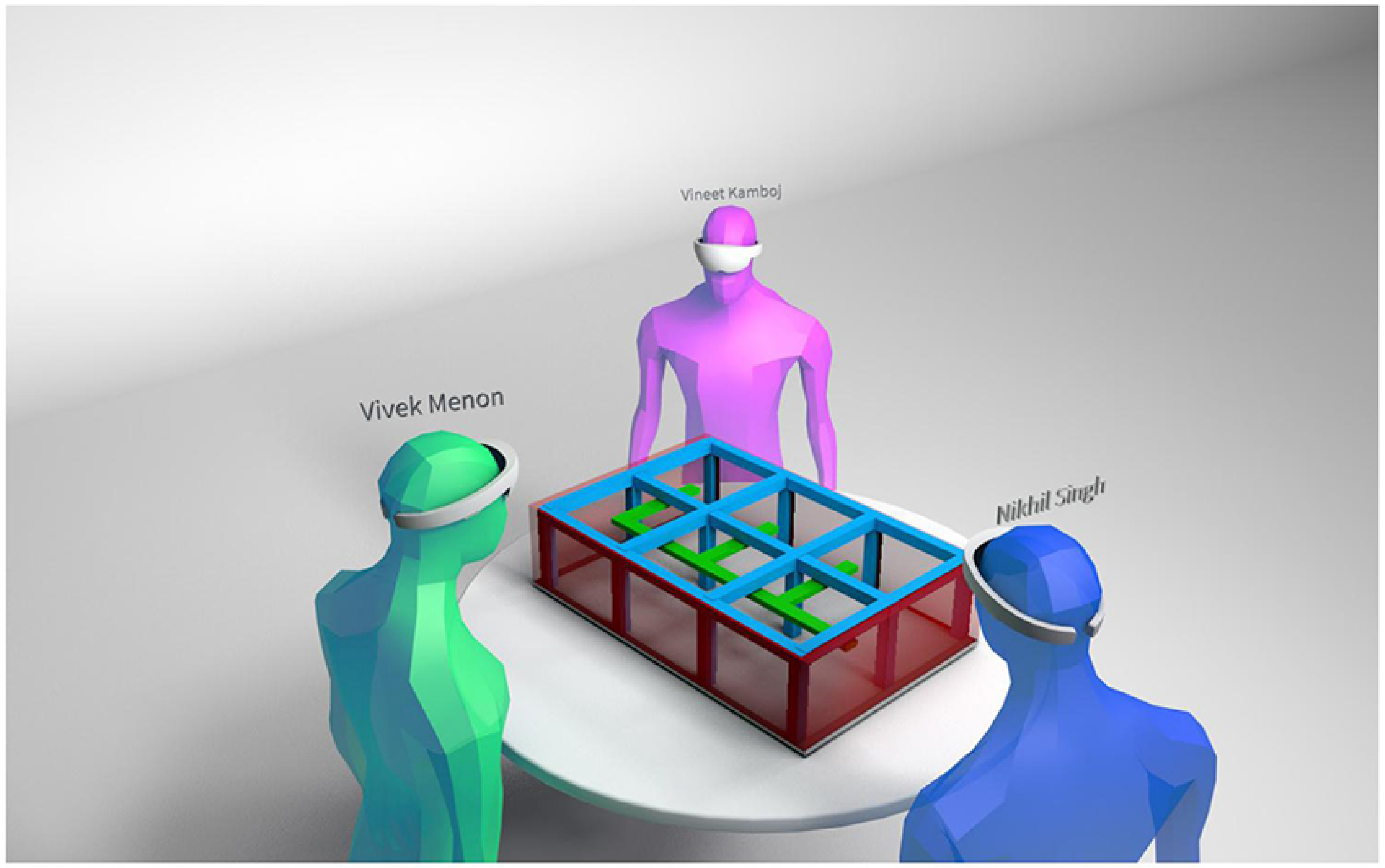


Fig. 5.57: *Collaborators change the layer opacity to view hidden elements.*

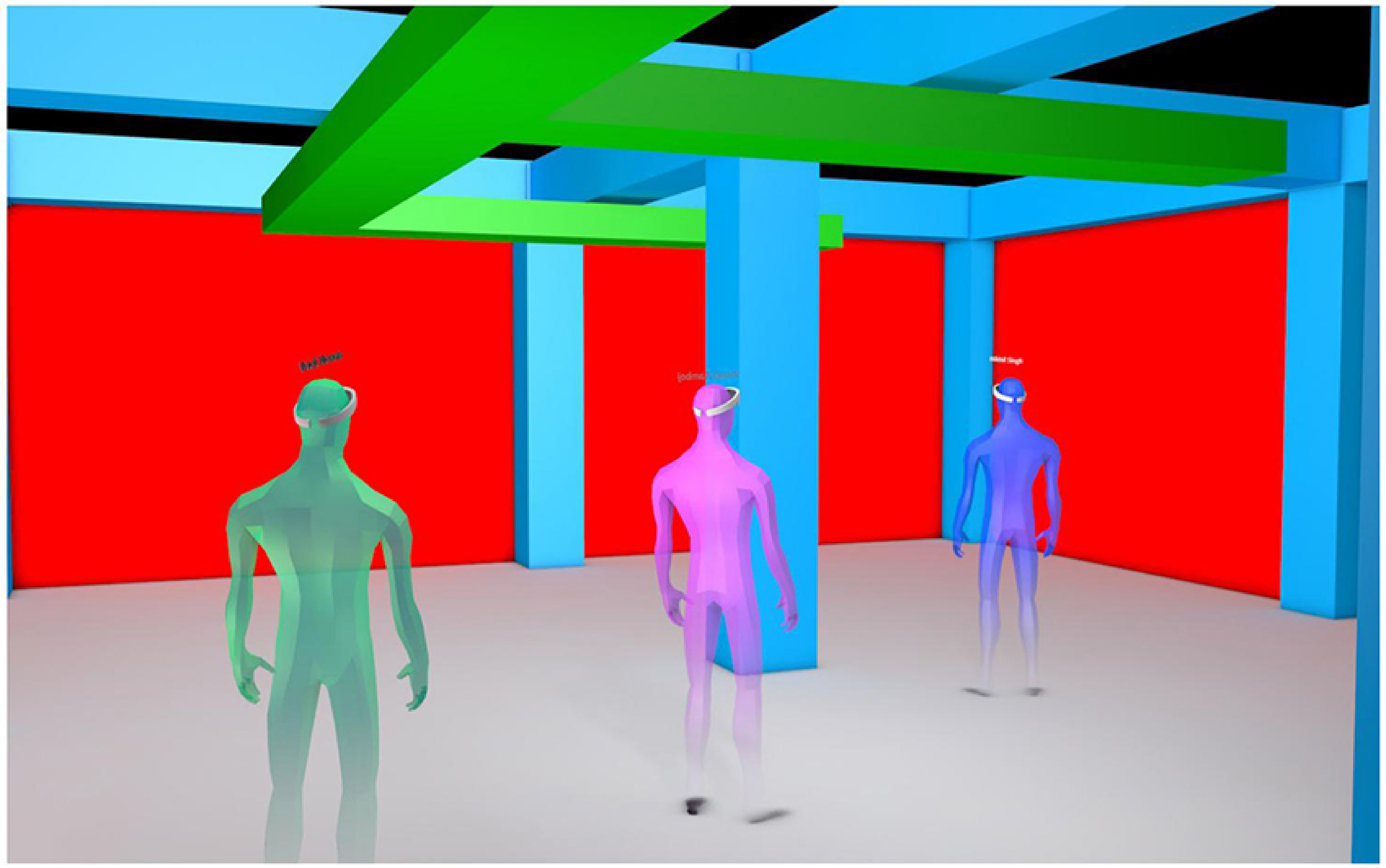


Fig. 5.58: *The collaborators switch to 1:1 scale of the structure they made to view the space in actual scale.*

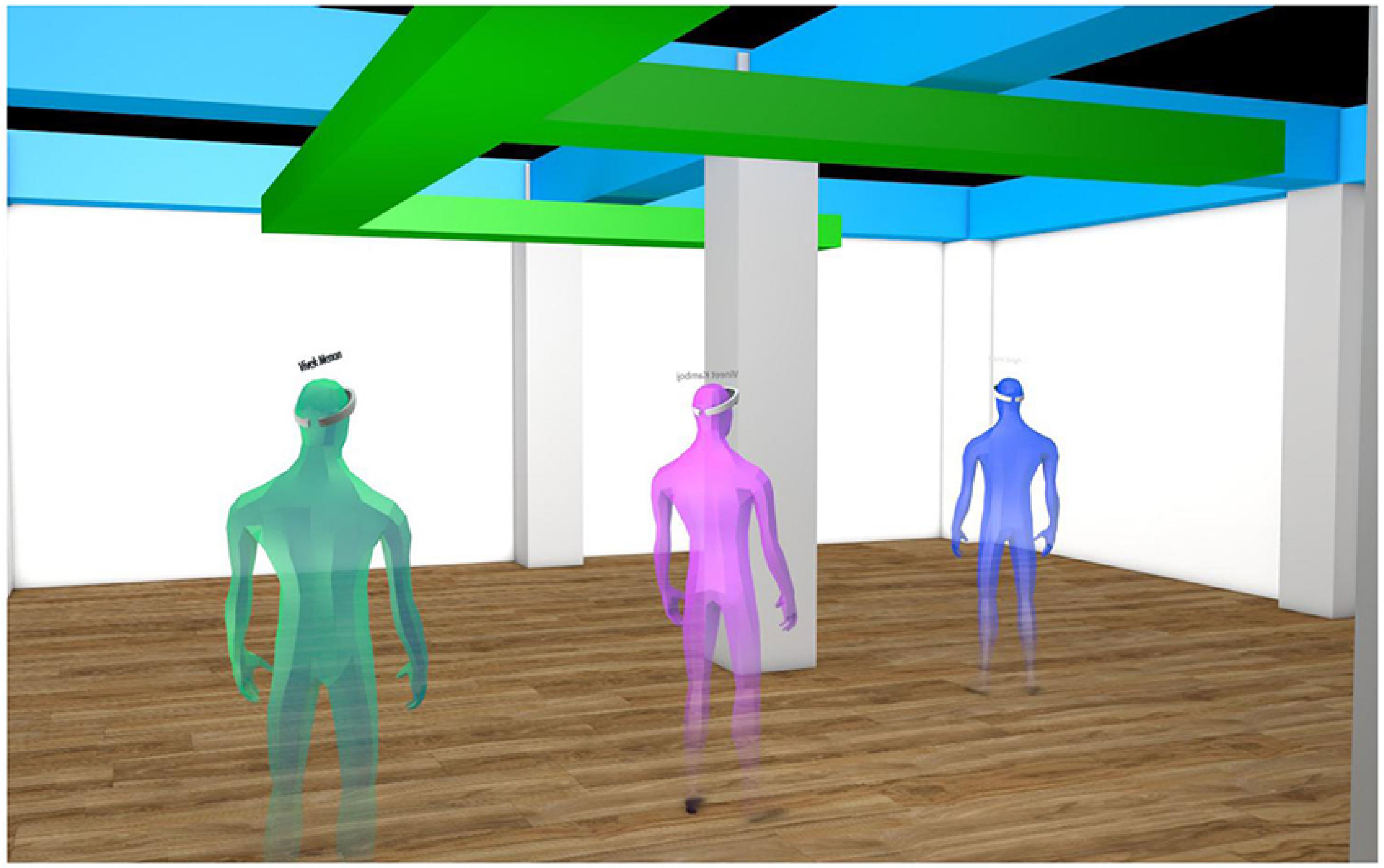


Fig. 5.59: *Collaborators change the properties of the structure in 1:1 scale. Here we see the floor and wall color have been changed.*

6 Prototype

6.1 Phase 1

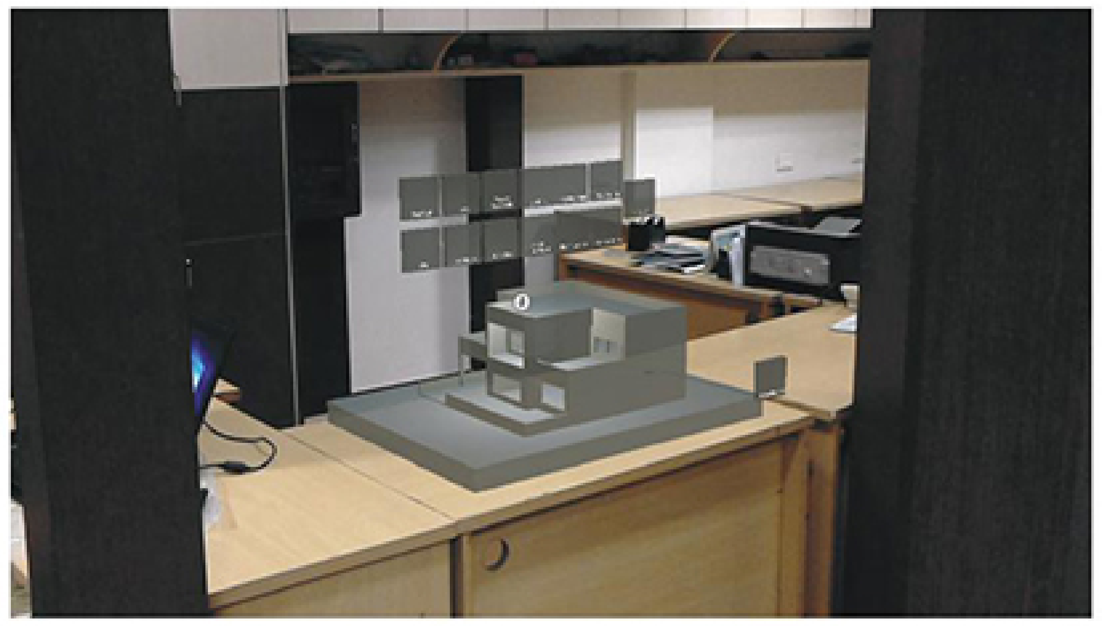


Fig. 6.1:
Initial prototype without a table.

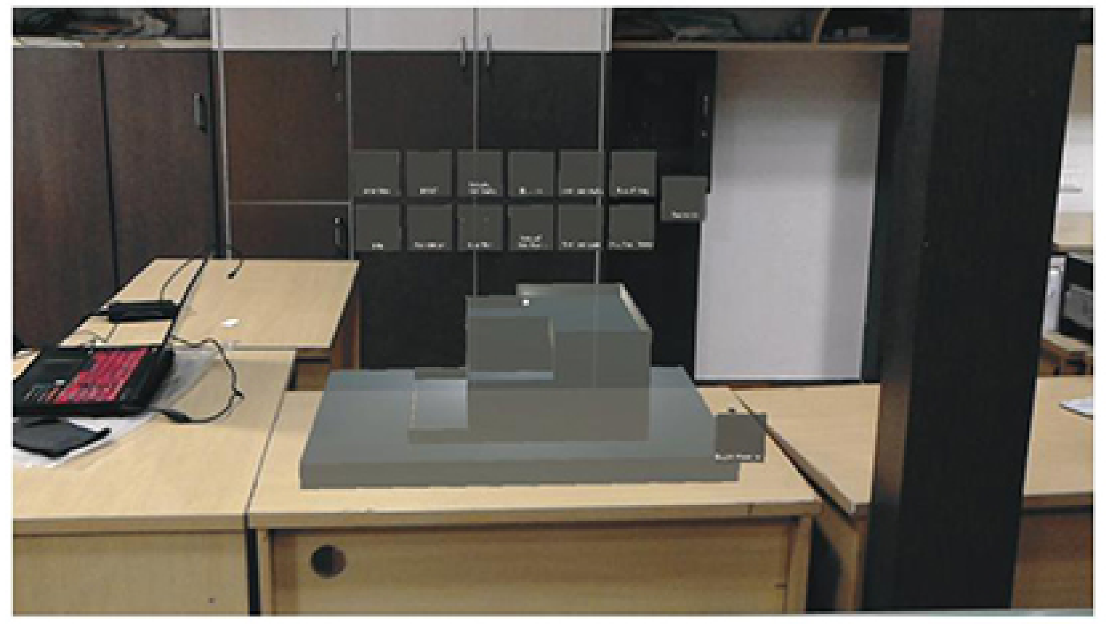


Fig. 6.2:
Layer toggle button above the model

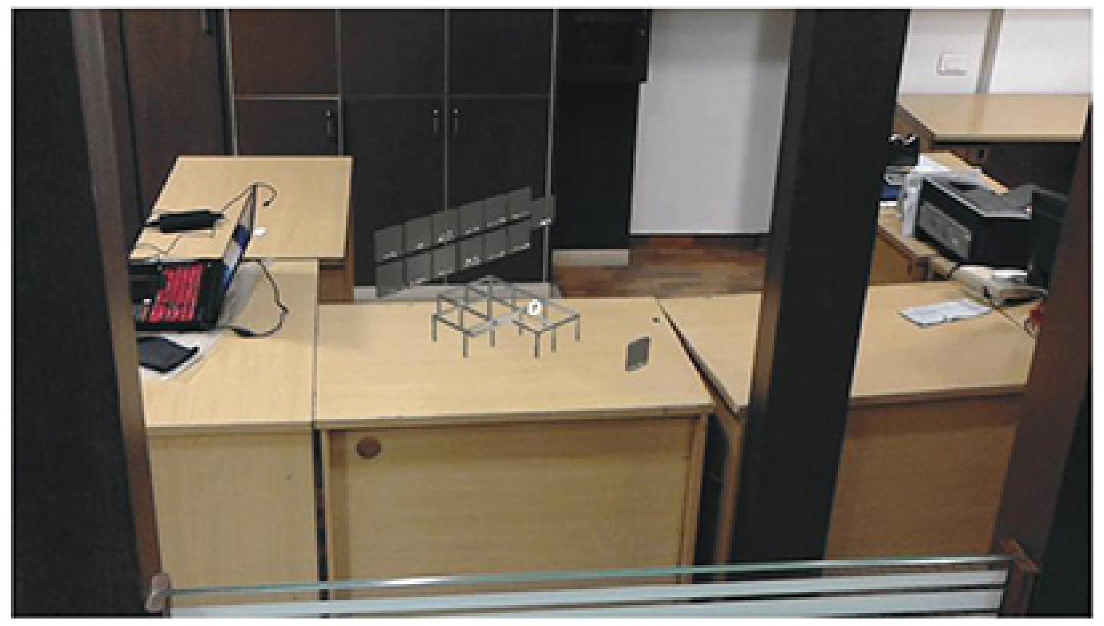


Fig. 6.3:
Structural layer isolated

Fig. 6.4:
Local collaboration on HoloLens

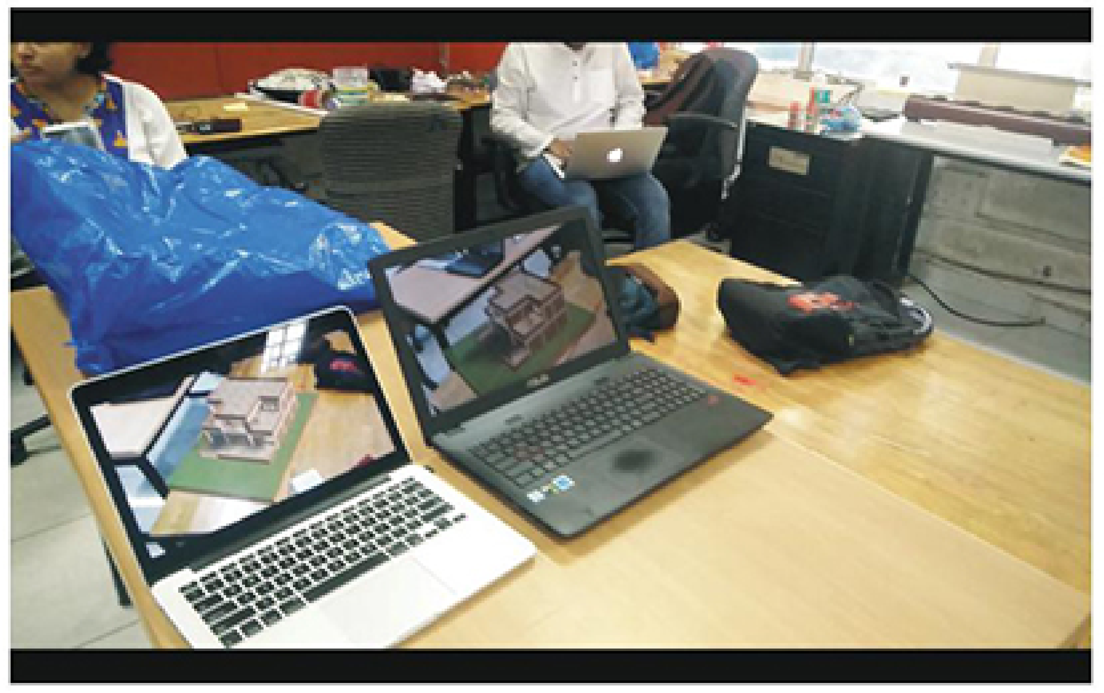


Fig. 6.5:
Screens showing view of both the collaborators

Fig. 6.6:
Local collaboration on HoloLens

Note: All images are taken directly through Microsoft HoloLens

6.2 Phase 2

Fig. 6.7: *Login Panel*

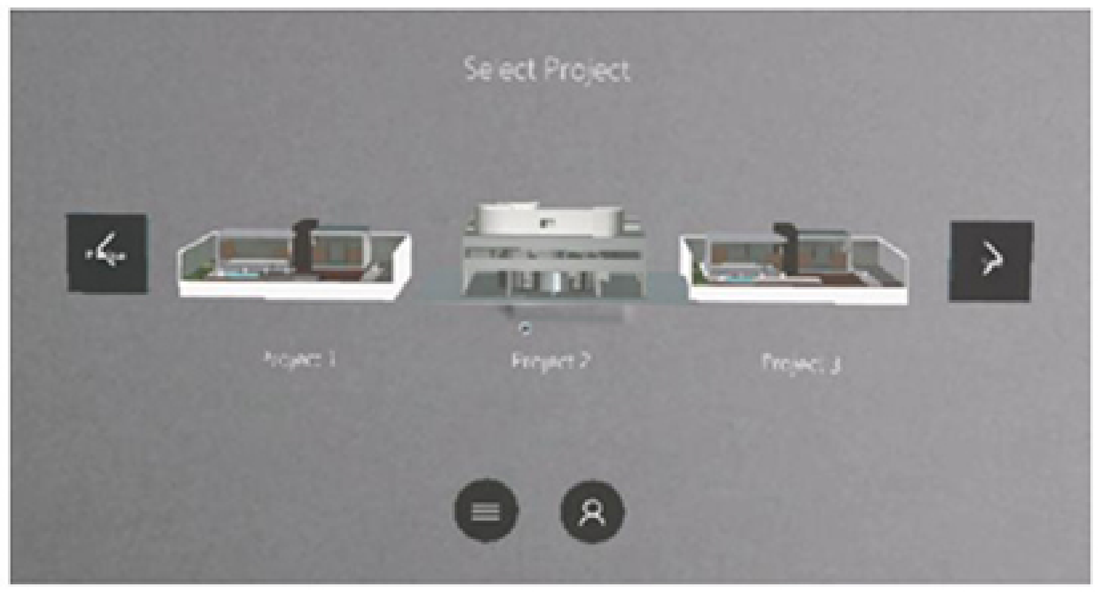


Fig. 6.8: *Project Selection scene*

Fig. 6.9: *Table placement using spatial Mapp.*

Fig. 6.10: *Collaboration station*

Fig. 6.11: *Main Menu*

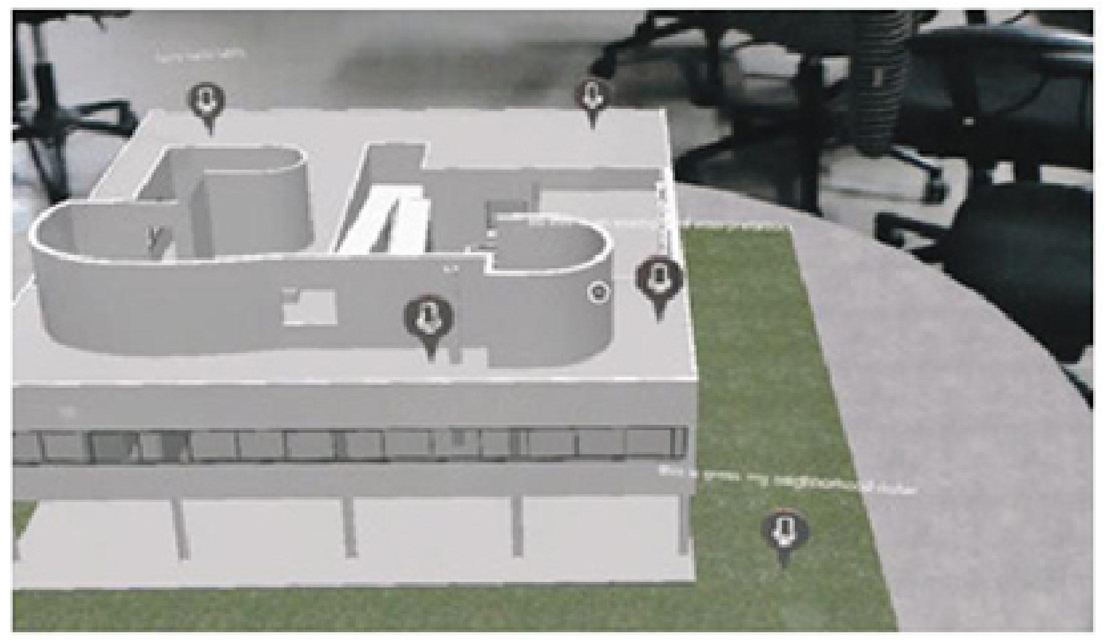


Fig. 6.12: *Annotations in remote collaboration*

Fig. 6.13: *Local Collaboration*

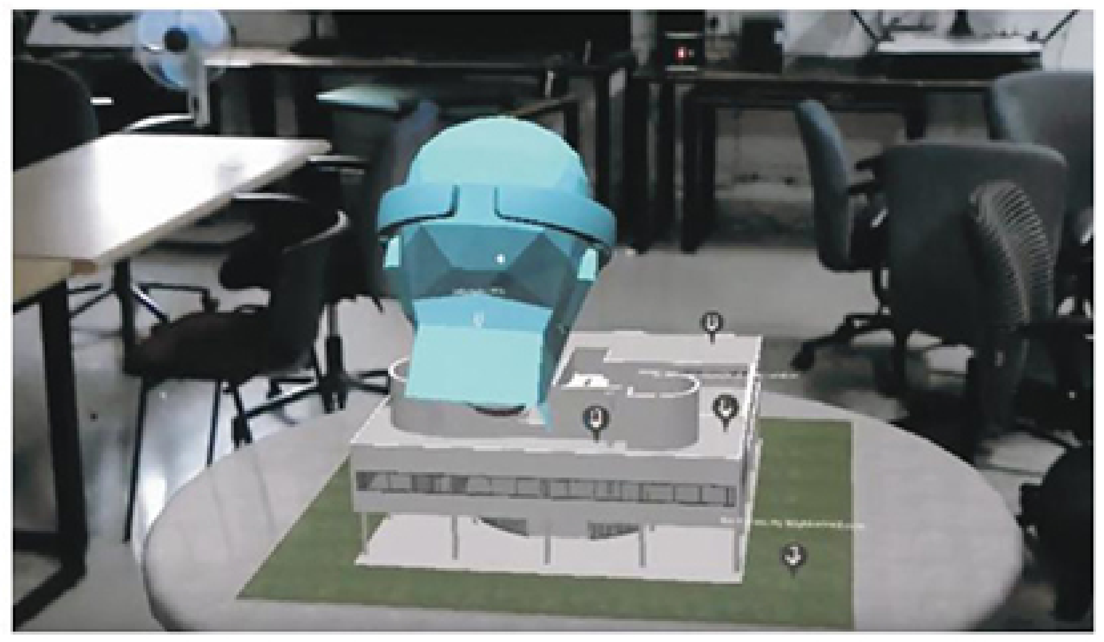


Fig. 6.14: *Virtual avatar looking at the model*

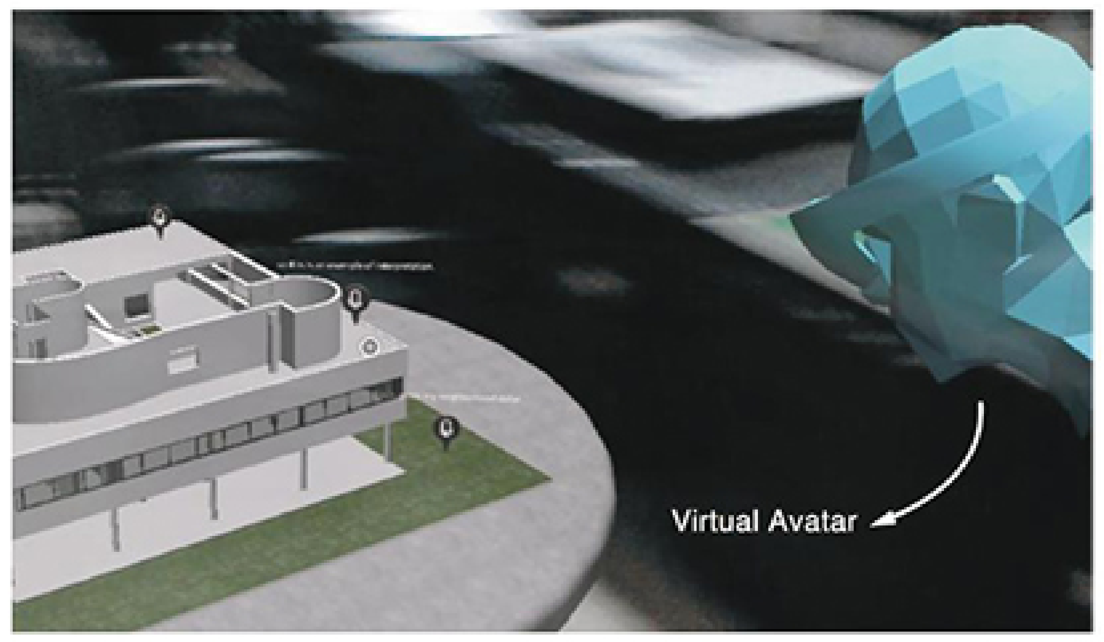


Fig. 6.15: *Virtual avatar looking at the model*

Note: All images are taken directly through Microsoft HoloLens

6.3 Phase-3

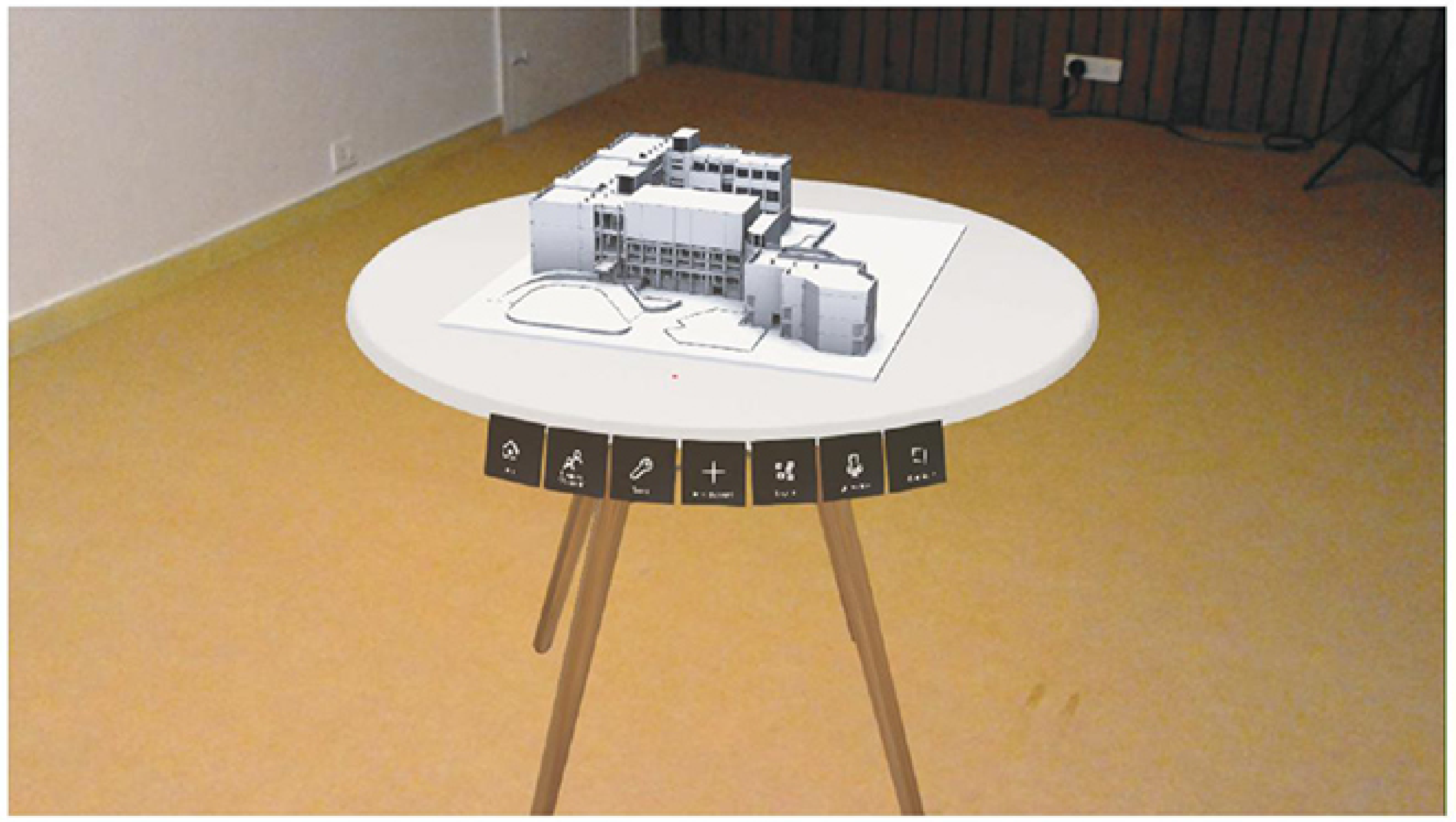


Fig. 6.16: *New Collaboration station for better visibility, Author*

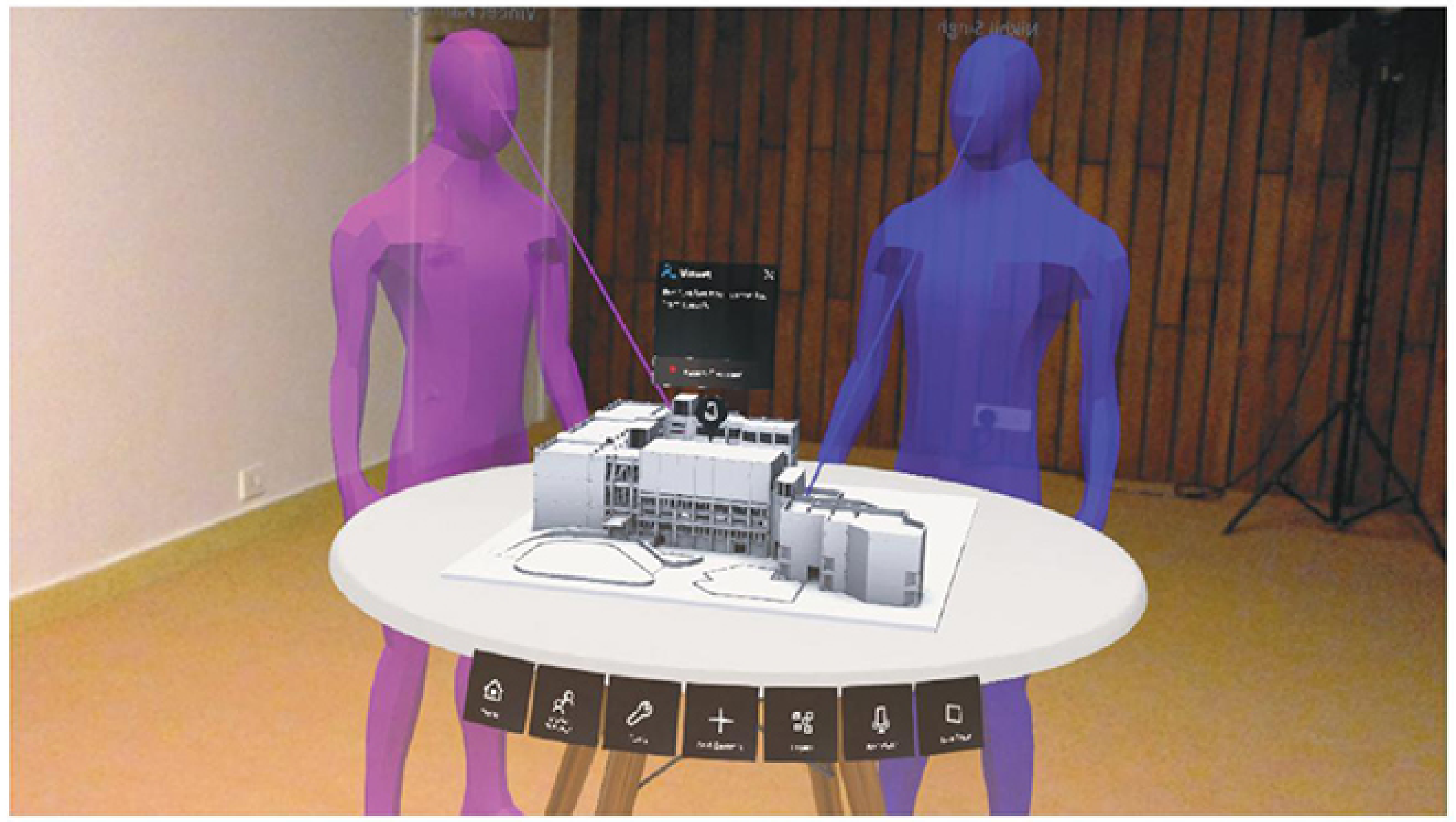


Fig. 6.17: *Virtual avatars connected remotely*

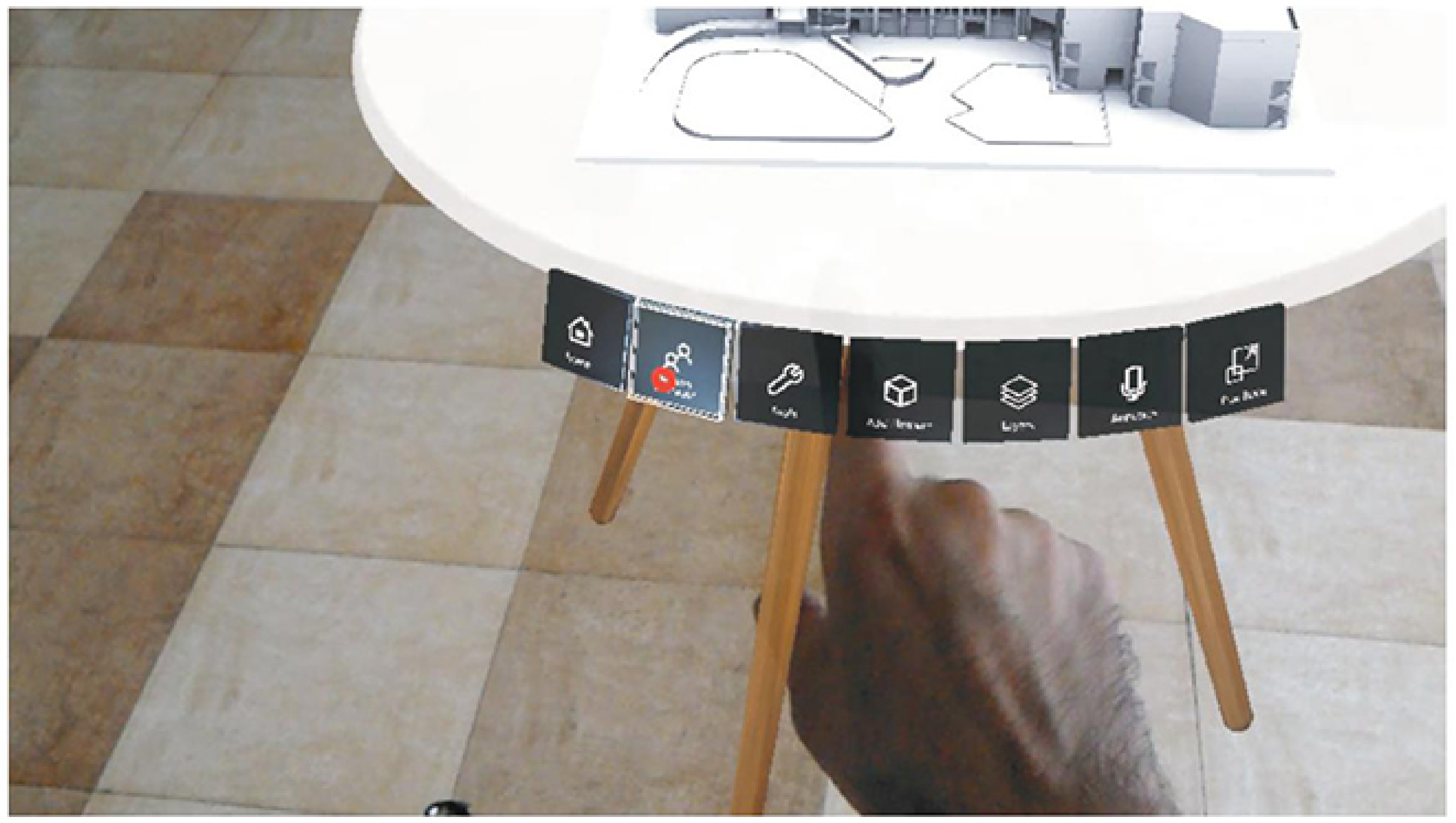


Fig. 6.18: *Main Menu (7 items)*

Fig. 6.19:*Section Tool*

Note: All images are taken directly through Microsoft HoloLens

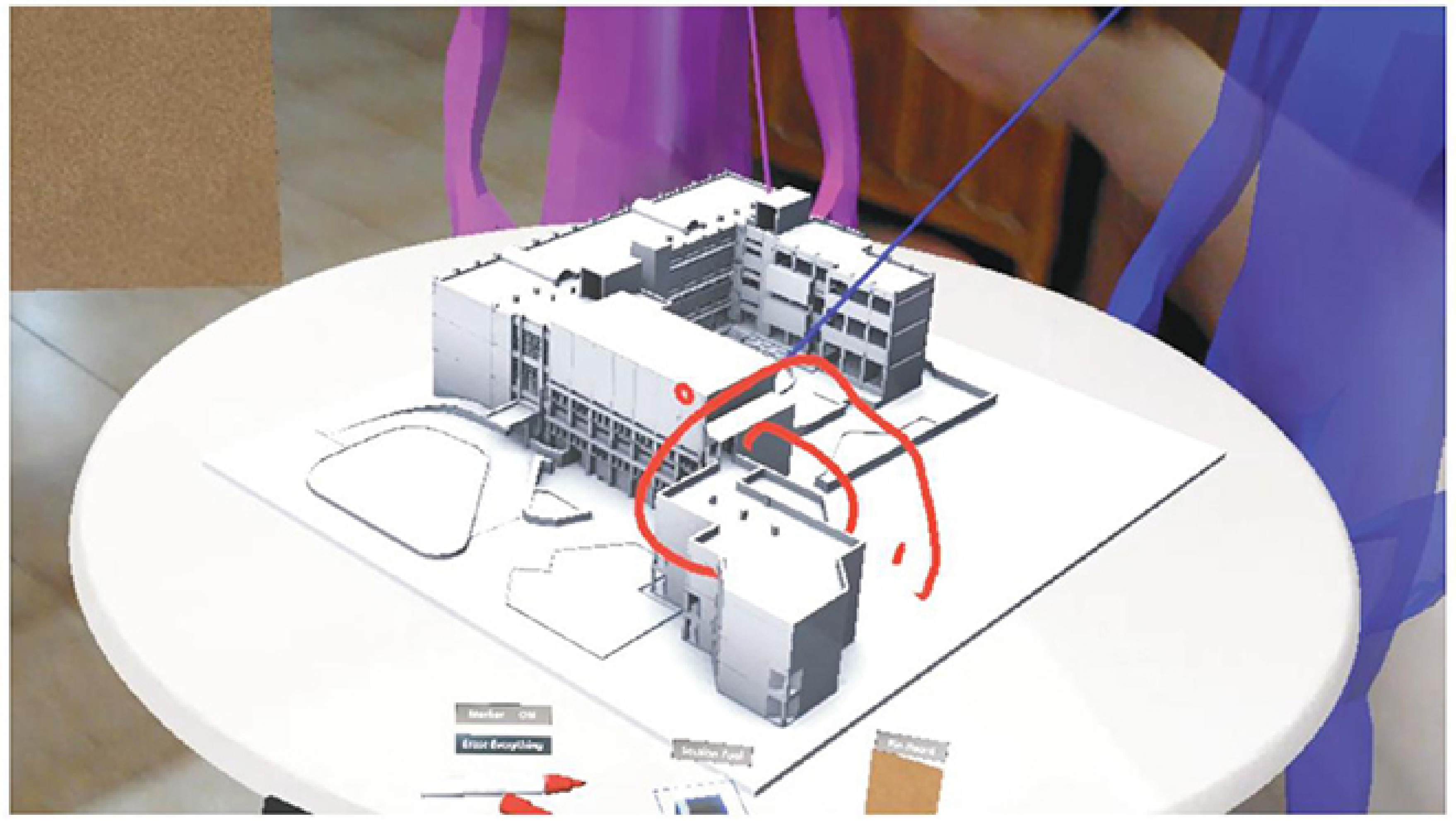


Fig. 6.20: *Draw tool in red*

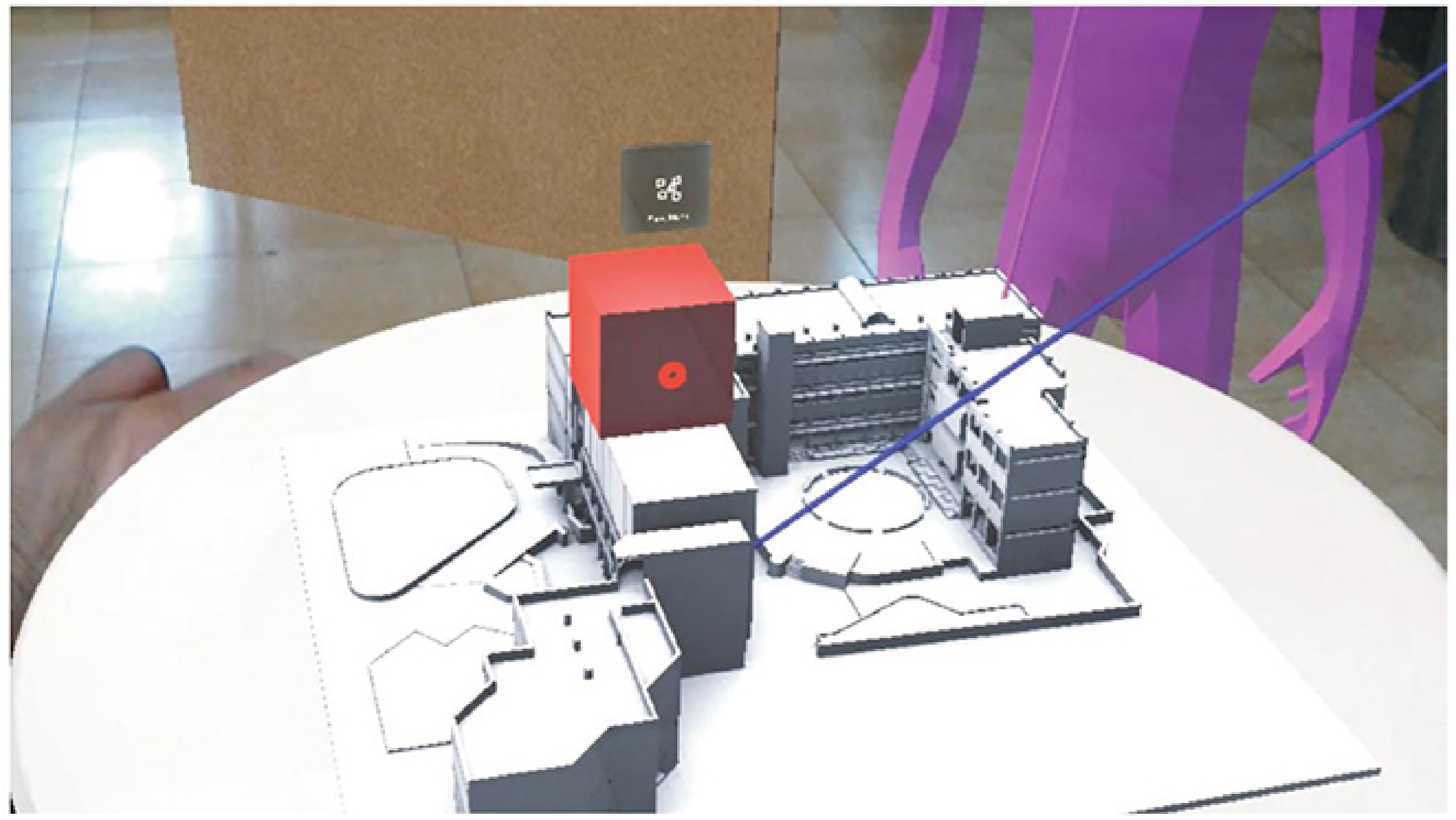


Fig. 6.21: *Adding an element*

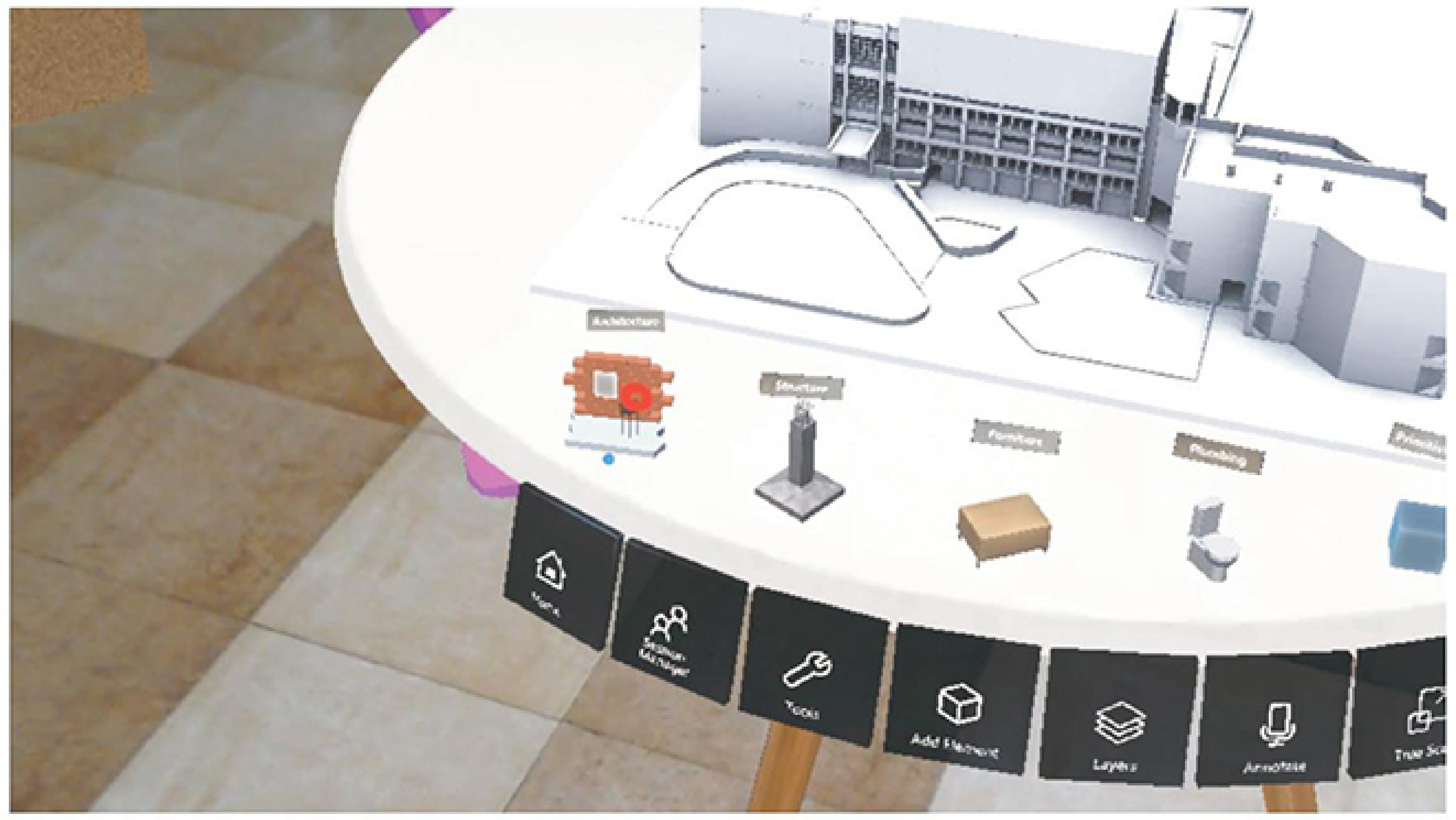


Fig. 6.22: *Add elements submenu*

Fig. 6.23: *True Scale Mode with teleportation*

Note: All images are taken directly through Microsoft HoloLens

7 Mixed Reality Ecosystem Design

In an office environment all the collaborators in architectural project work on their desktop machines/ laptops. The collaborators view and modify the data (3D model, Drawings, etc.) generated on the desktop machines using the collaborative platform on Hololens. The collaborative platform allows working in mixed reality environment, but finally, the work is carried forward on the desktop machines/ laptops. To complete the collaboration cycle, the amendments made during the collaborative session should be accessible outside the mixed reality environment. The ecosystem connects the workstation and Hololens which allows the user to transfer the data from the Desktop machine to the HoloLens and the modified data back from HoloLens to the desktop computer. The data exchange from Hololens to a desktop computer includes the modified 3D Model, Annotations, etc.

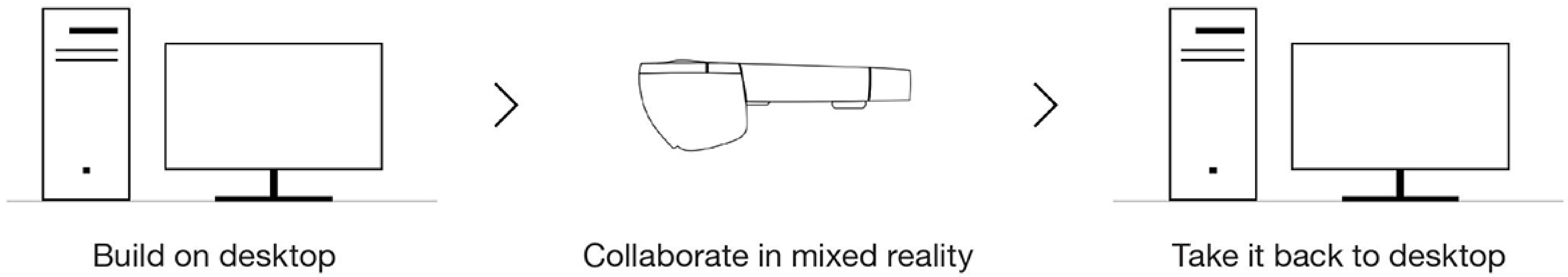


Fig. 7.1: *Ecosystem Goal*

7.1 Proposal

The ecosystem consists of a desktop companion application, an online database, and a HoloLens application. The desktop companion app (DCA) is a Universal Window Platform application which allows the user to upload the data set to the online database and to download the modified 3D model and other resources including comments to the desktop machine. The online database acts as a repository of all the data and a medium which allows sharing of the data generated during the collaborative session.

7.2 Working

Collaborator A (Architect) and collaborator B (Structure Engineer) are working on a shared 3D model on the cloud database. Both the collaborators are remotely located and are using a windows desktop computer. Both the collaborators push the changes made by them in the 3D model using the Desktop Companion App on their respective desktop machines. Both the participants start the collaborative platform on Hololens. The HoloLens app updates the model with the changes pushed by both the collaborators. The collaborators perform activities to manipulate the resource which is then synced up on the cloud database. Both the collaborators get back to their desktop machines to resume the work after the session is over. Now they can see all the changes, comments, decisions, etc. through the desktop application made during the collaboration session.

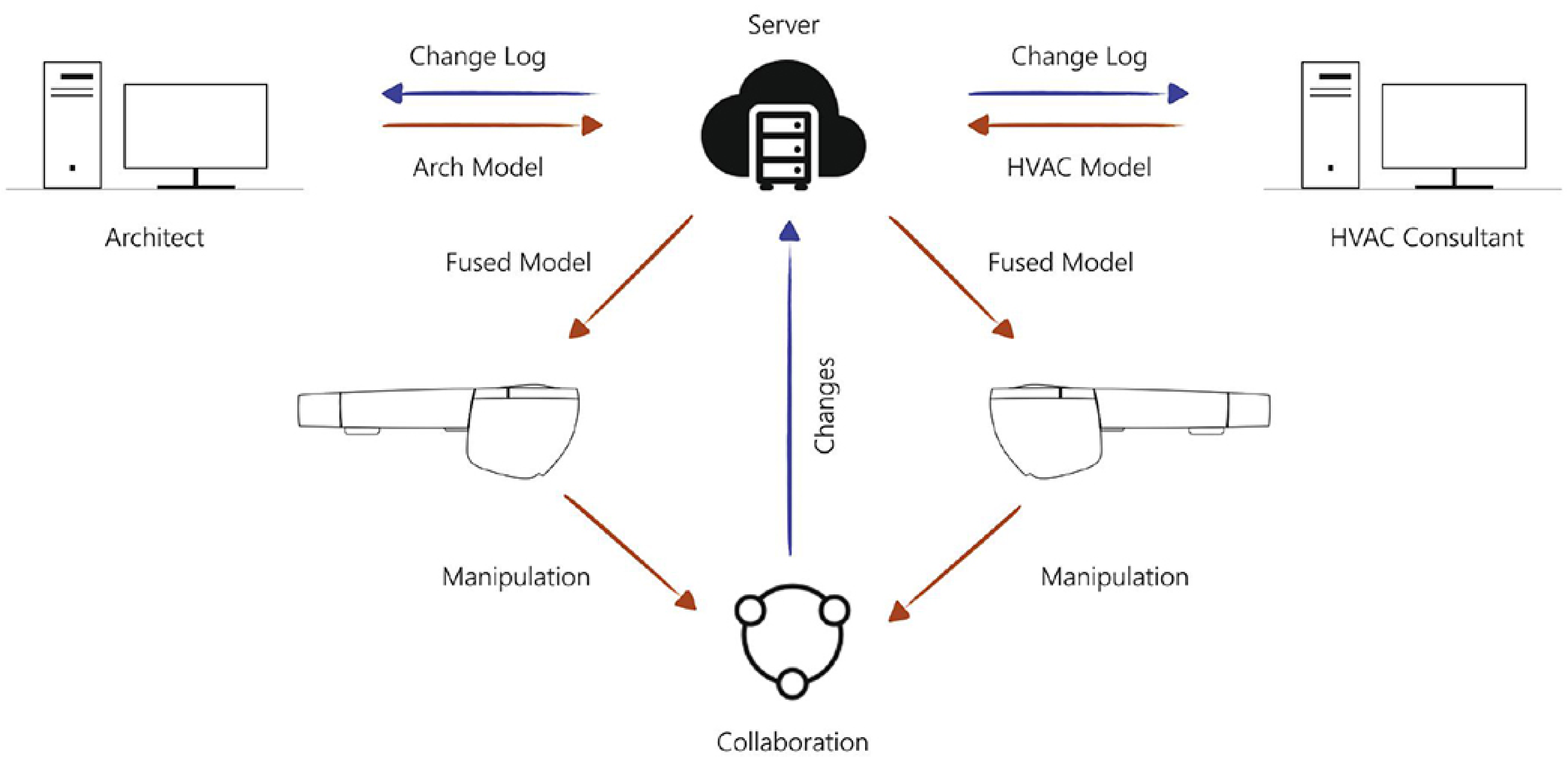


Fig. 7.2: *Mixed reality ecosystem data exchange map*

7.3 Use of ecosystem in architectural project

Concept Stage
The concept stage includes idea-ting on the space design and site planning of the project. Massing using blocks on the site model (physical models), concept sketches, virtual 3D models showing masses on the site are some of the few techniques used during the concept evolution stage. A 2D site plan and a scaled virtual and physical model of the site is made to visualize the topography details, which also include the adjacent structures around the construction site. This stage mainly contains architects more than one if multiple architects are working on the project and the client sometimes. The collaborators generate data in the form of sketches, 2D drawings and virtual 3D models which can be uploaded using the DCA. The collaborators can now perform manipulation and have discussions utilizing the generated content in mixed reality environment through the collaborative platform. The collaborators located remotely can explain the concepts and discuss with other collaborators without building physical 3D Models.

Drafting and Drawing stage
In this stage, 3D modeling of the structure and drafting of approval and GFC (Good For Construction) drawings run simultaneously. Multiple meetings held during this stage, are for discussing design changes and ideas. Other collaborators like structural engineers, Plumbing, and electrical consultants come in the scenarios at this stage. In the case of BIM, all these collaborators work on a central shared file, but on individual layers as per the model element authority. For, eg. The electrical consultant works on the electrical layer of the drawings as well as the 3D model. In this case/scenario mixed reality collaborative platform is used for discussions and changes on the virtual 3d model with the remote collaborators.

Construction Stage
In this stage all the collaborators in the project are active. A lot of design changes occur during the construction stage. Regular review meetings between the collaborators are held to discuss the project status, construction issues, and design changes. All the

changes in the design during such sessions lead to revision is the 2D drawings and 3D models. The collaborative platform record all the changes made in the model and all other activities performed during the collaborative session. These recordings are similar to minutes of meetings and are critical to the revisions which are to be corrected or added to the data sets as per the discussion during the session. The DCA acts as a repository of all the activities performed during the collaborative session on Hololens. All the collaborators can access to different meetings and review the changes those made during each course.

Requirements
The Hololens application keeps the data secure by using an instance of the original 3D model for manipulation purposes. Many activities performed during the session on Hololens generate data used for making changes/ revisions in 2D and 3D data. These activities include Modification in 3D model, Comments, Annotations, etc. Once the user is out of the mixed reality environment, he/she will have to perform revisions back on the desktop machine. All the data generated in the Hololens session should be available at the central working system to implement necessary changes in the original data. The DCA allows seamless exchange of data between the Hololens and main workstation. Other than that DCA acts as a repository of all the data and a management tool for managing different running projects. It also serves as a communication platform for asynchronous communication between the collaborators.

Concept Map

A cloud database keeps a record of all the changes made during the session. The DCA allows the user to view all the changes stored in the cloud database on a desktop computer. The user works on a central shared model, and the DCA enables the user to push the data to the cloud server. The HoloLens application syncs the data from the cloud database. Collaborates make changes to the updated data on Hololens. The Hololens app again synchronizes all the data back to the server, which updates on the DCA.

Use Cases

To check the current status of 2D as well as 3D data
The DCA allows the user to view the latest as well as older version of the data. The user can track the history of changes made to a particular data set which enhances the visibility of a project.

To access all the changes and information from past sessions
The application is primarily is based on the concept of meetings. By meetings we mean, the collaborative sessions performed on the Mixed Reality Platform. All the data generated in these sessions are stored and managed as different sessions in the DCA which allows the user to quickly access the changes made and decisions taken in past meetings.

Manage different projects and collaborators
Every Project is created and administered by a single collaborator. The admin decides the authorities given to all the collaborators. These authorities dictate who can make changes in a particular layer of the model. Managing also includes creating, archiving, modifying and deleting of projects.

Upload and download data
One of the primary use cases of the application is to push and pull changes in the shared data. DCA allows easy upload and download of data like Drawings, pictures, and 3D models of elements, etc.

7.4 Information Architecture

The information architecture of the companion application consists of two major parts. The first part is where the user can create a new project and the second part is where the user can view and manage the ongoing or complete projects.

The creation of project includes defining the project details and setting up the collaborators. The creator of the project adds the collaborators and determines the authorities of all the collaborators, depending on which they can contribute during the collaborative sessions. In the New project segment, the admin attaches the central 3D model of the structure which will be accessed by HoloLens as well.

The second part of the IA defines management and viewing tools for the ongoing projects. The projects section has two categories, Active and archived projects. Projects while are complete can be moved to the archived class. Every project consists of a Session Manager, a collaborator panel, discussion channels, Drawings, 3D element Library and the central Model of the project.

The Session Manager is like a File Cabinet which contains files called Sessions of every collaborative session happened in the past. Every session folder has all the information and data generated and used during the collaborative session. The data consists of a 3D model, Manipulation activities in the name of changelogs, annotations, and comments. The collaborator section lists down the details of all the collaborators in the project and their authority levels. These can be accessed by all but can be modified only by the creator of the project. In collaborative working asynchronous communication also takes place. The channels tab allows the users to create communication channels for defined discussions. E.g., a discussion channel of electrical and HVAC systems.

The drawings section acts as a repository of the drawings from all the concerned departments, i.e., Architecture, Electrical, Structural, HVAC, etc. These documents can be brought up during the collaborative sessions for discussion purposes.

3D element library consists of 3D models of various elements like a beam, door, column, window, furniture, etc. predefined for the project. After uploading the 3D items in the library, collaborators can utilize them during a collaborative session.

The central model viewer shows the current state of the shared model.

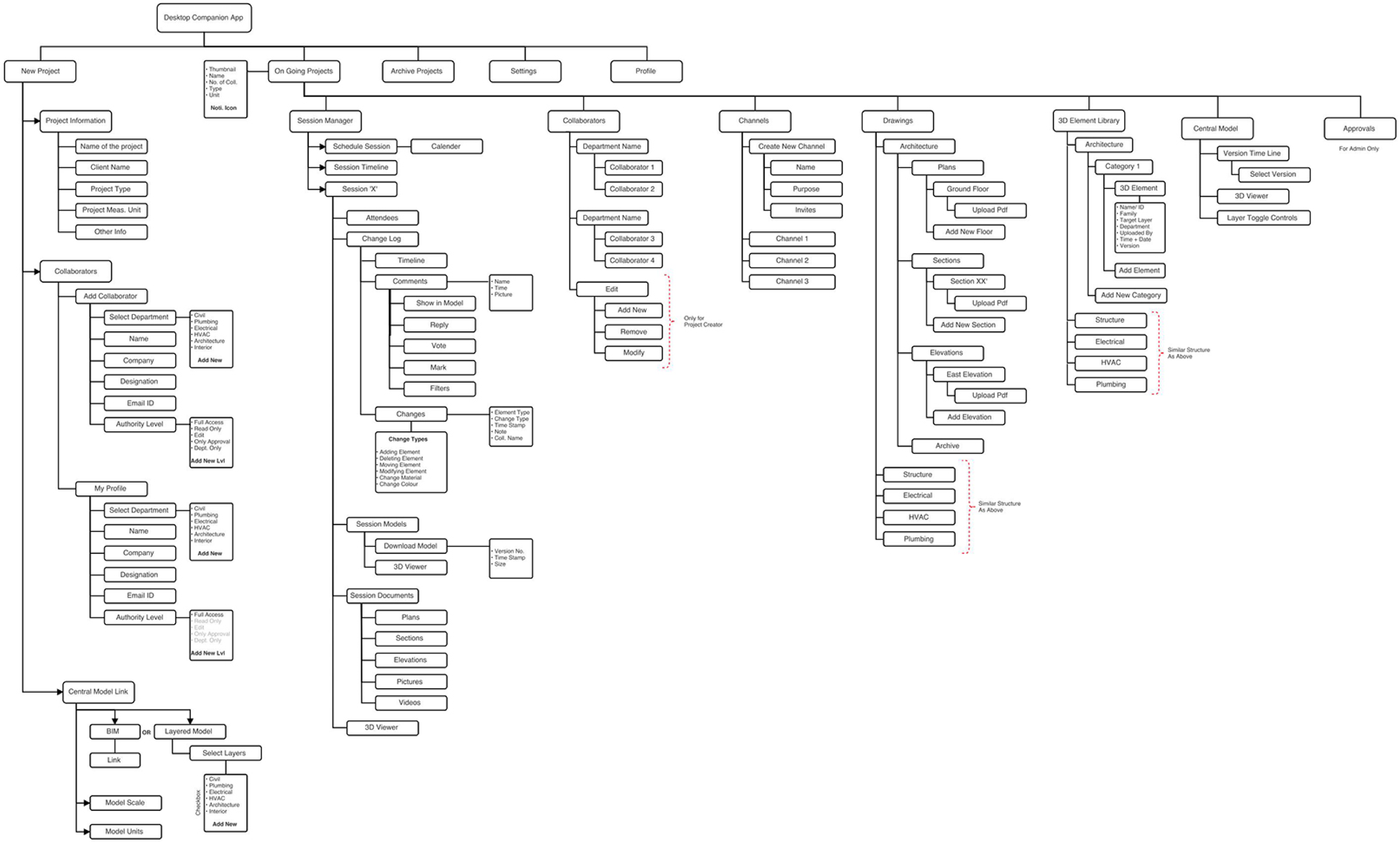


Fig. 7.3: *Desktop companion application Information Architecture*

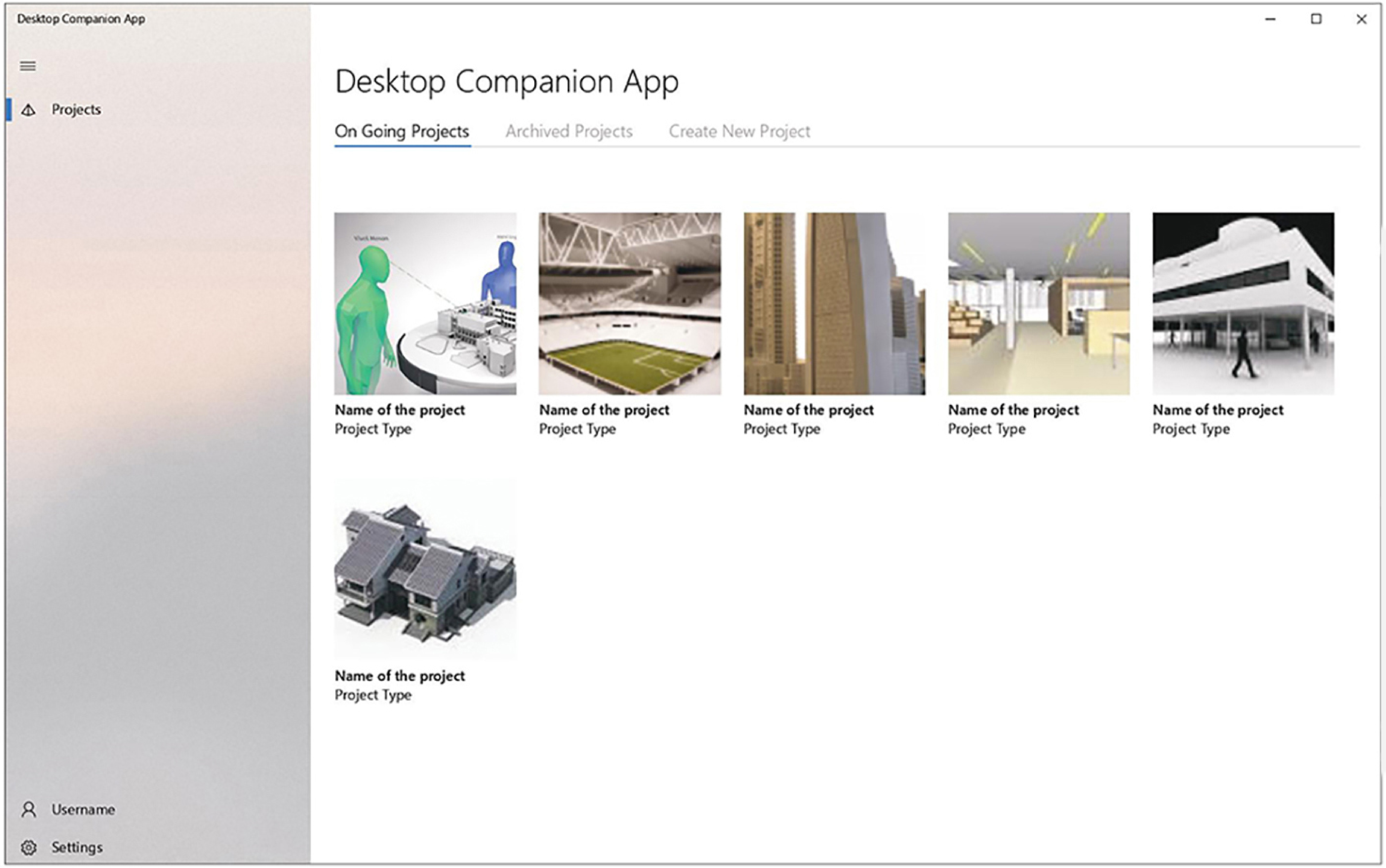


Fig. 7.4:

DCA Hi-Fi Proto - Landing Screen

7.5 High Fidelity Prototype

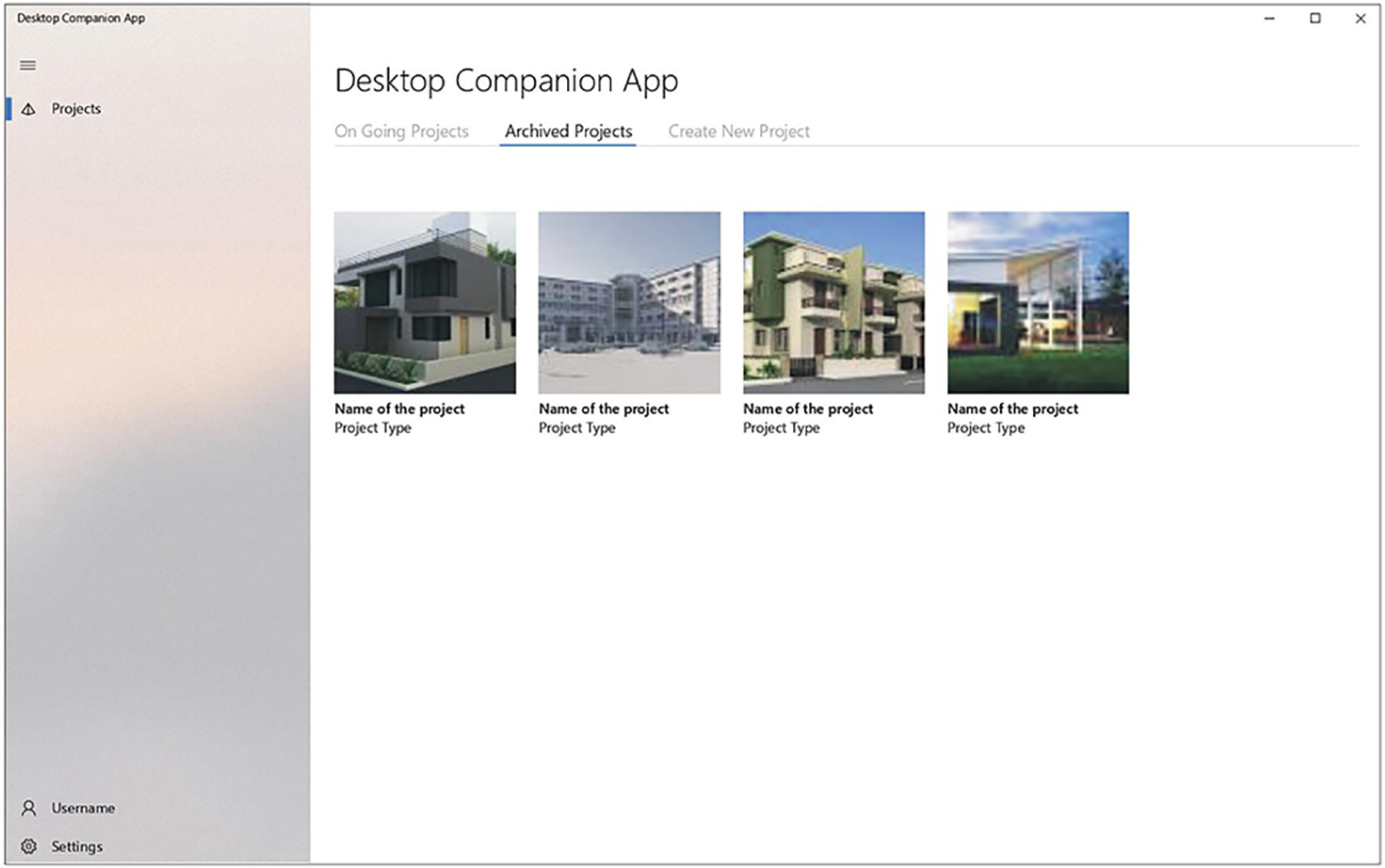


Fig. 7.5:

DCA Hi-Fi Proto - Archived Projects

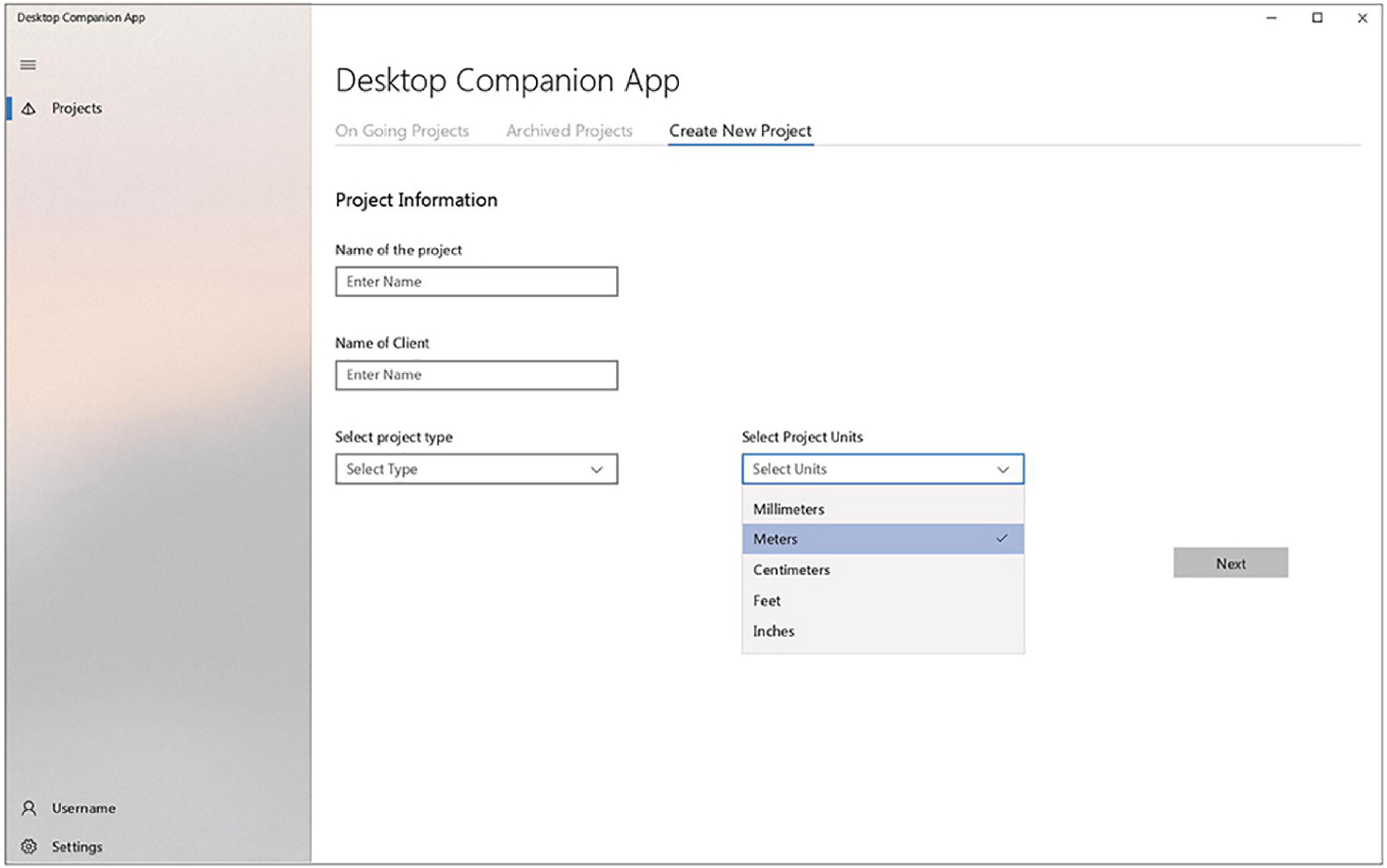


Fig. 7.6:

DCA Hi-Fi Proto - Create New Project > Project Information

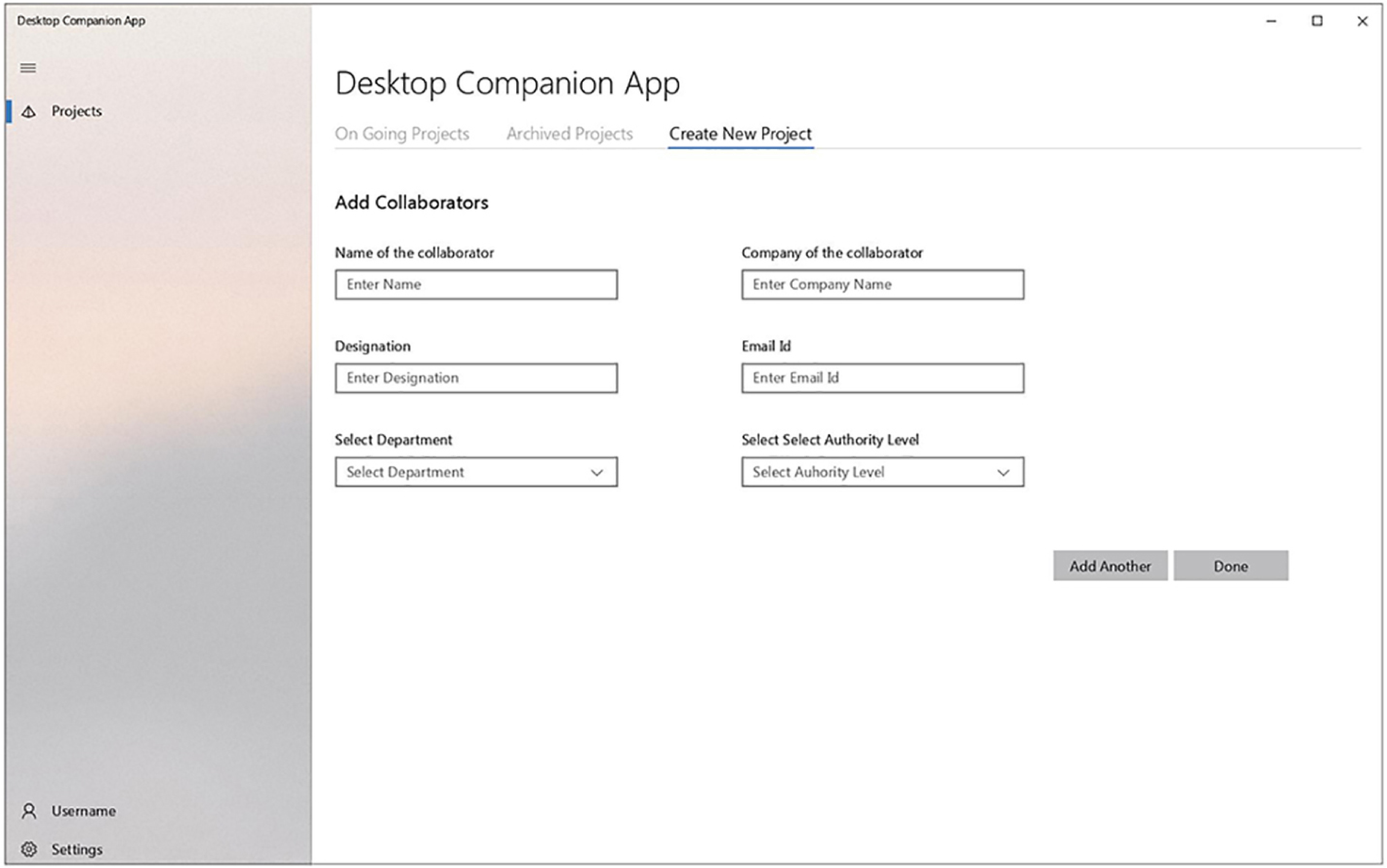


Fig. 7.7:

DCA Hi-Fi Proto - Create New Project > Add Collaborator

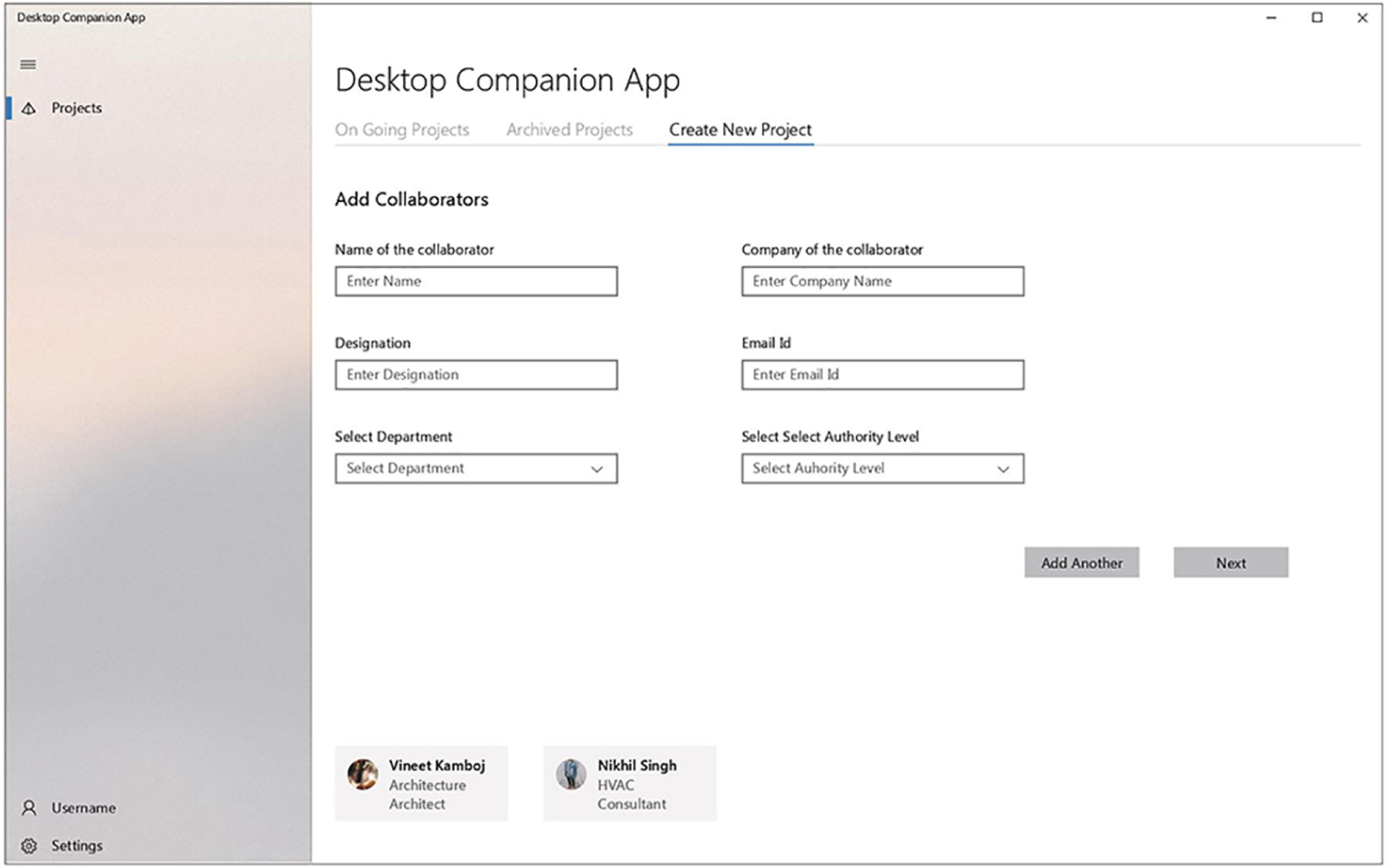


Fig. 7.8:

DCA Hi-Fi Proto- Create New Project > Add Another Collaborator

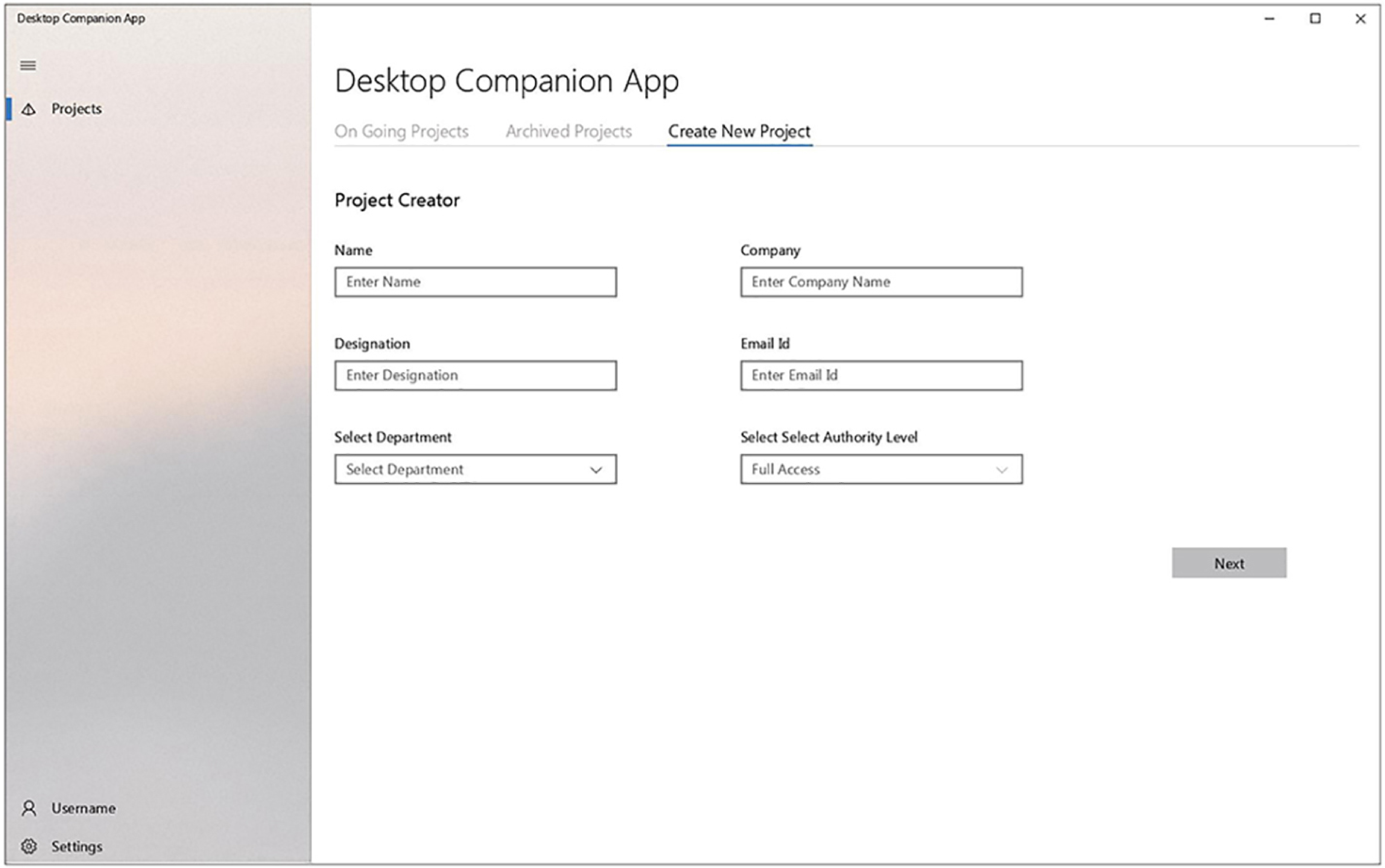


Fig. 7.9:

DCA Hi-Fi Proto - Create New Project > Creator Details

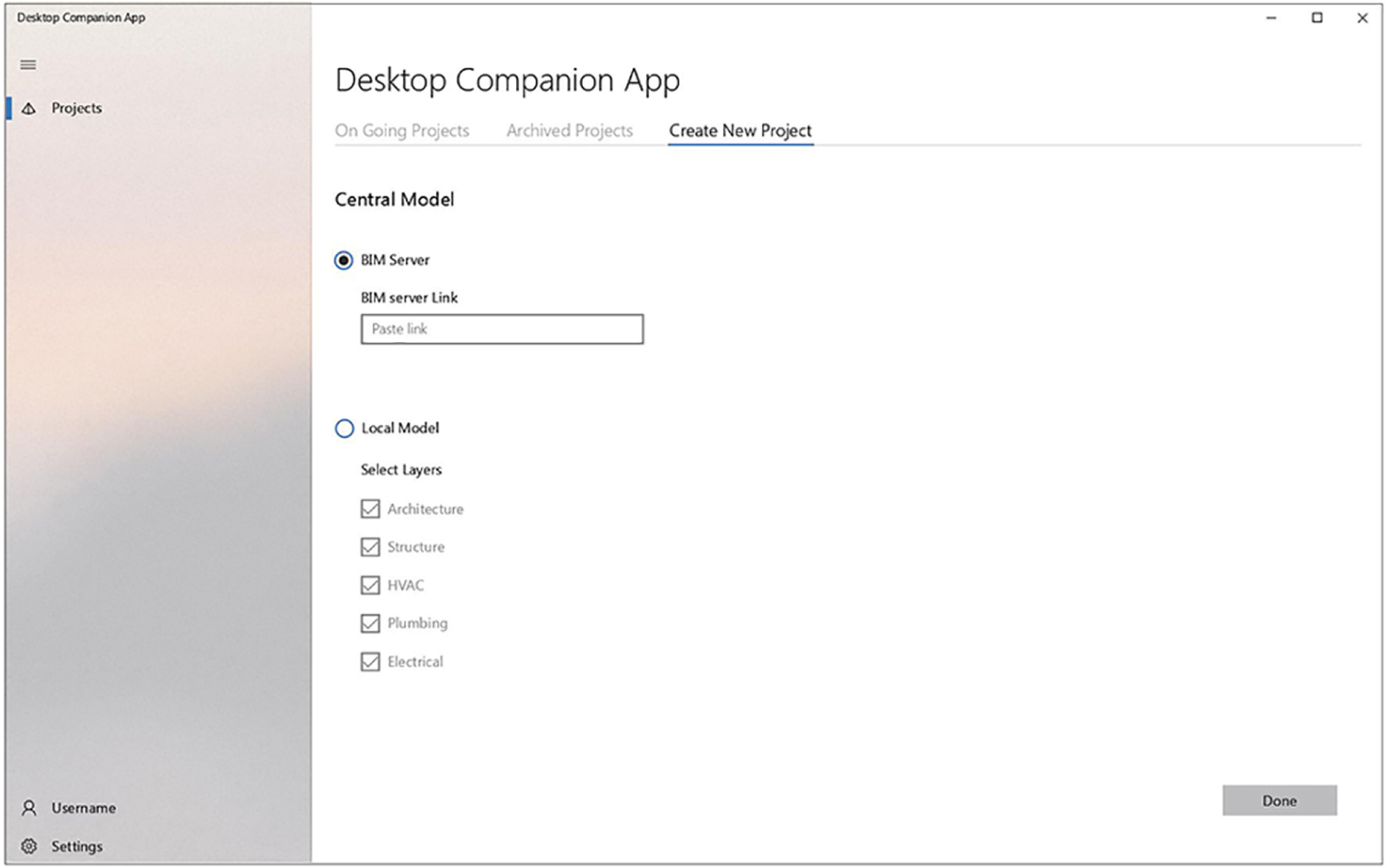


Fig. 7.10:

DCA Hi-Fi Proto - Create New Project > Link Model

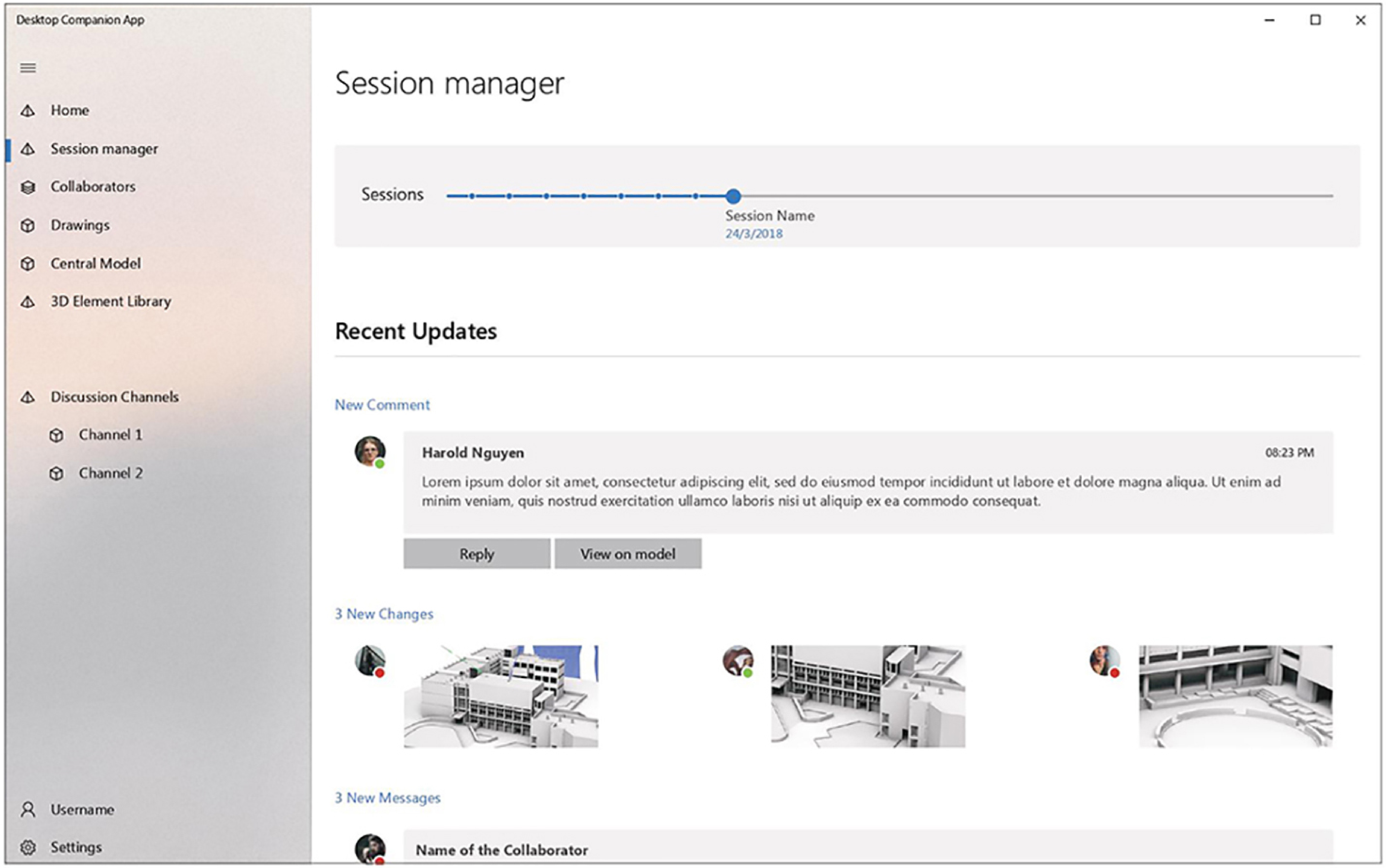


Fig. 7.11:

DCA Hi-Fi Proto - Session Manager

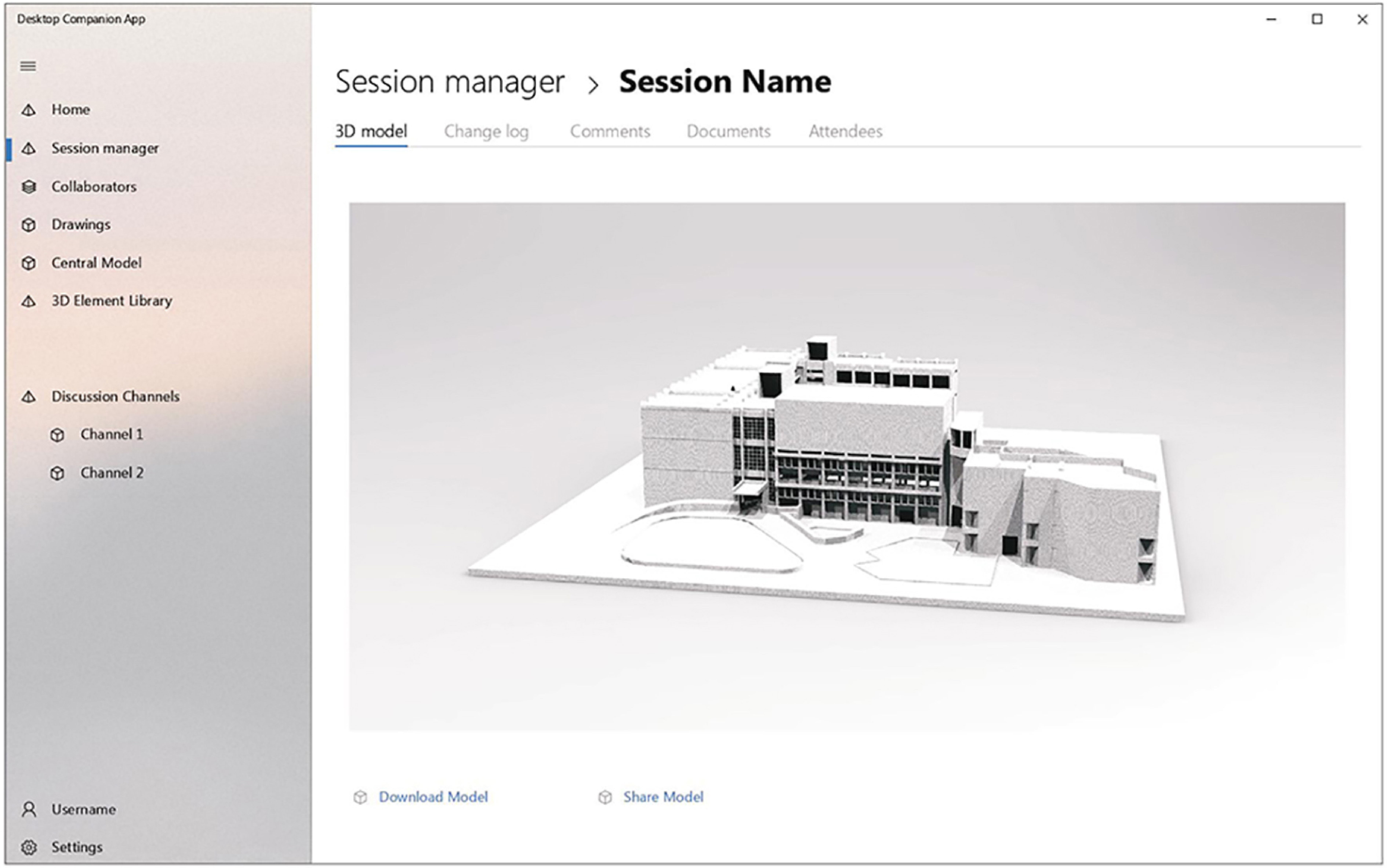


Fig. 7.12:

DCA Hi-Fi Proto - Session Manager > Session X > 3D Model

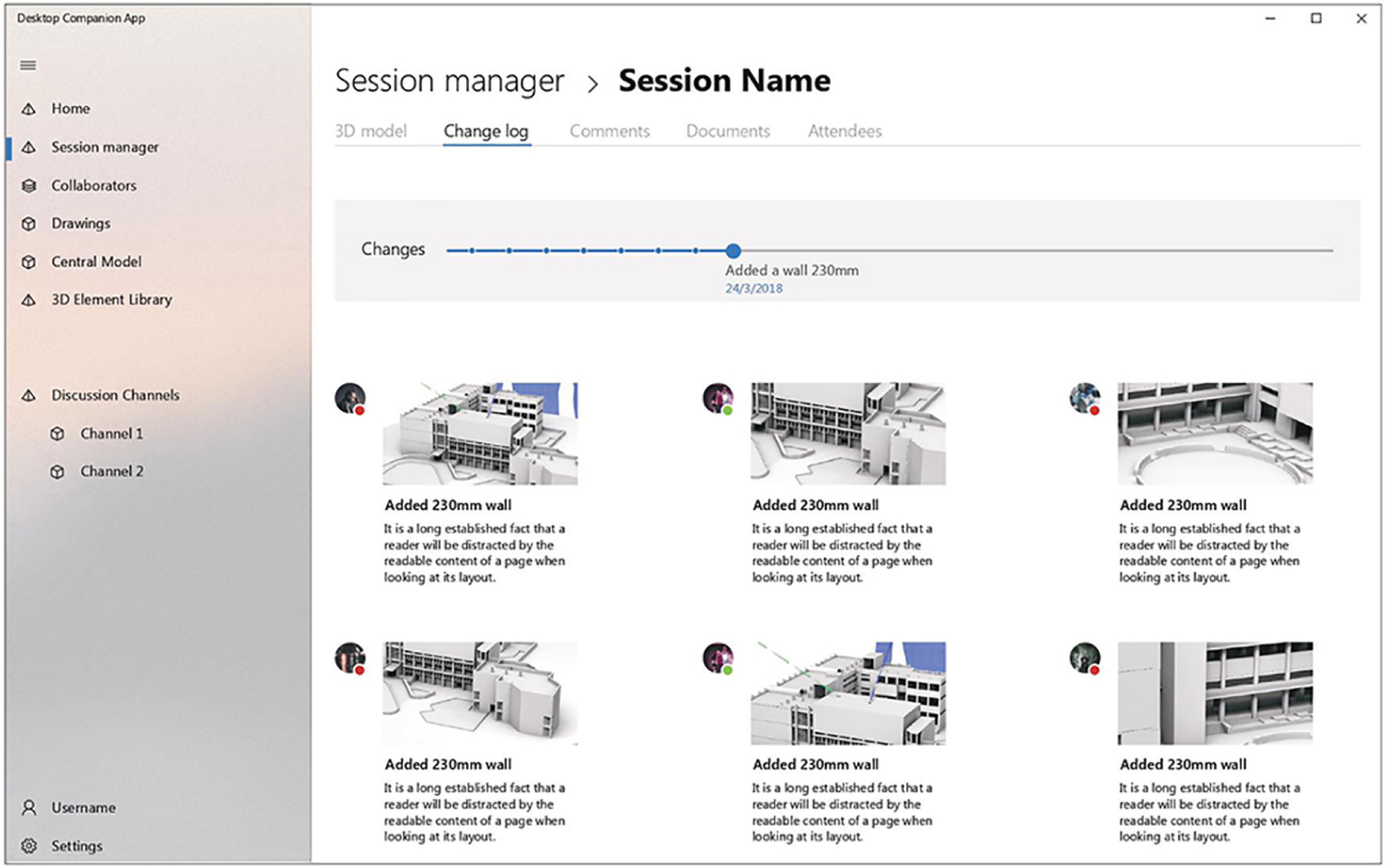


Fig. 7.13:

DCA Hi-Fi Proto - Session Manager > Session X > Change Log

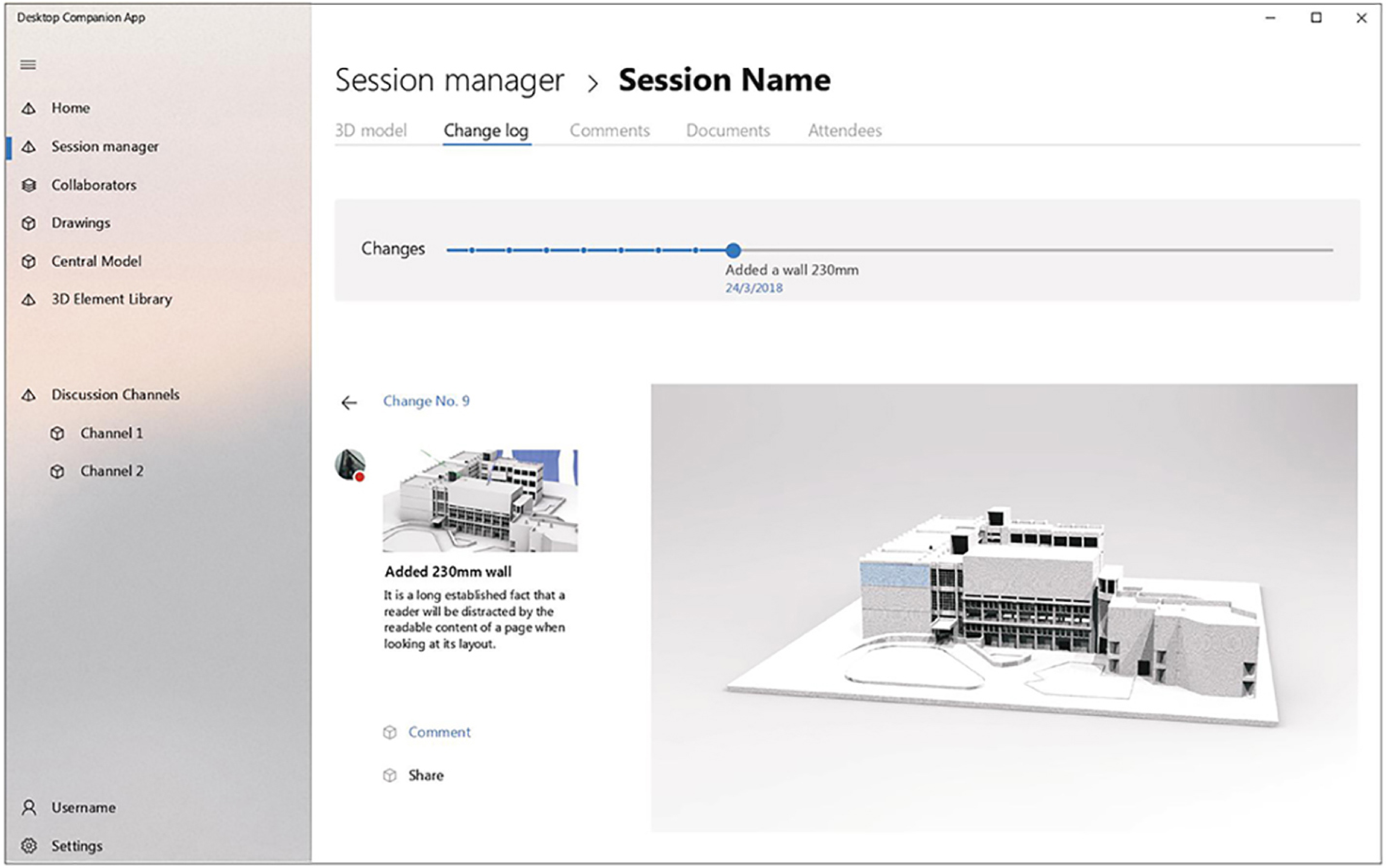


Fig. 7.14:

DCA Hi-Fi Proto - Session X > Change Log > Log 9

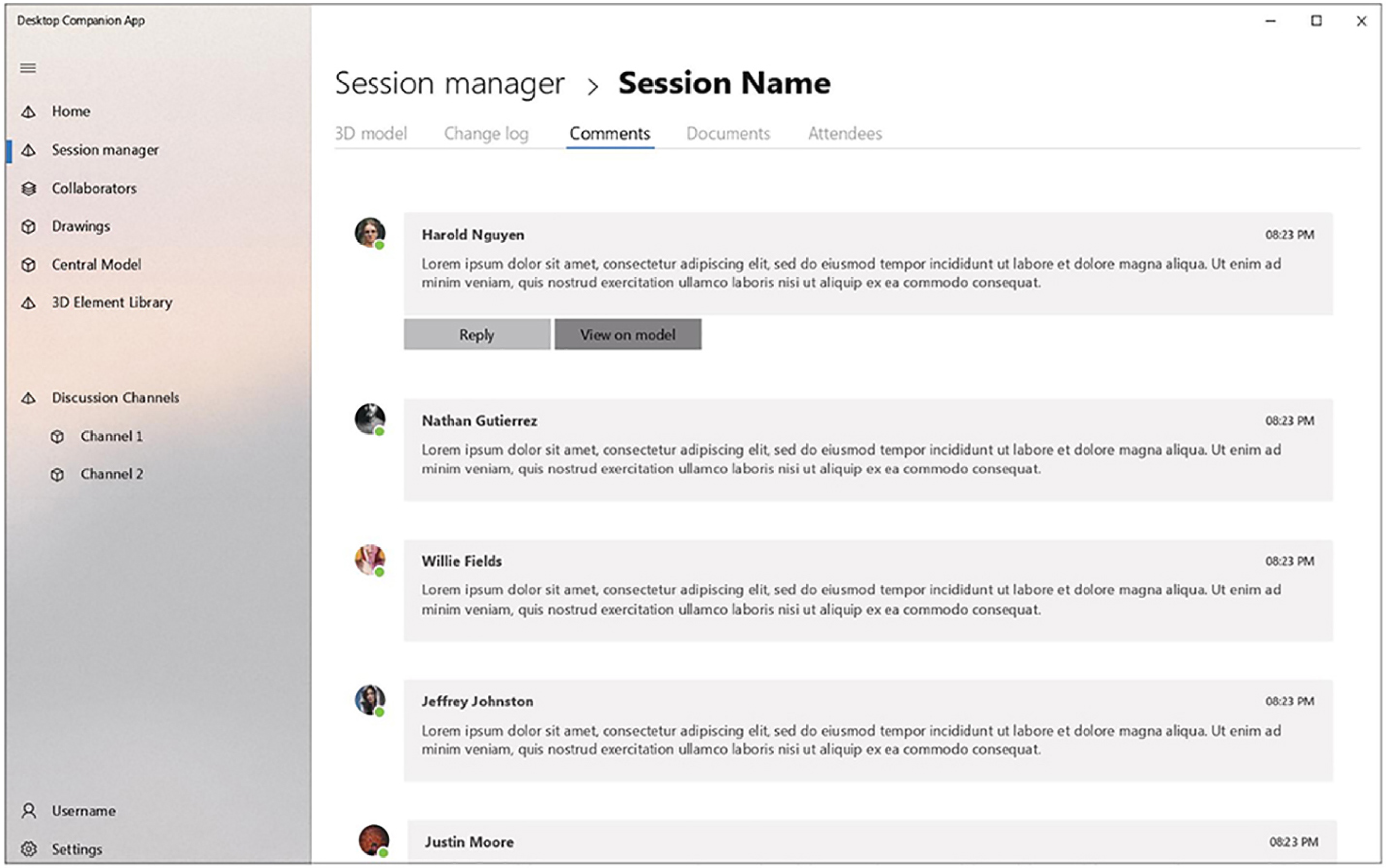


Fig. 7.15:

DCA Hi-Fi Proto - Session Manager > Session X > Comments

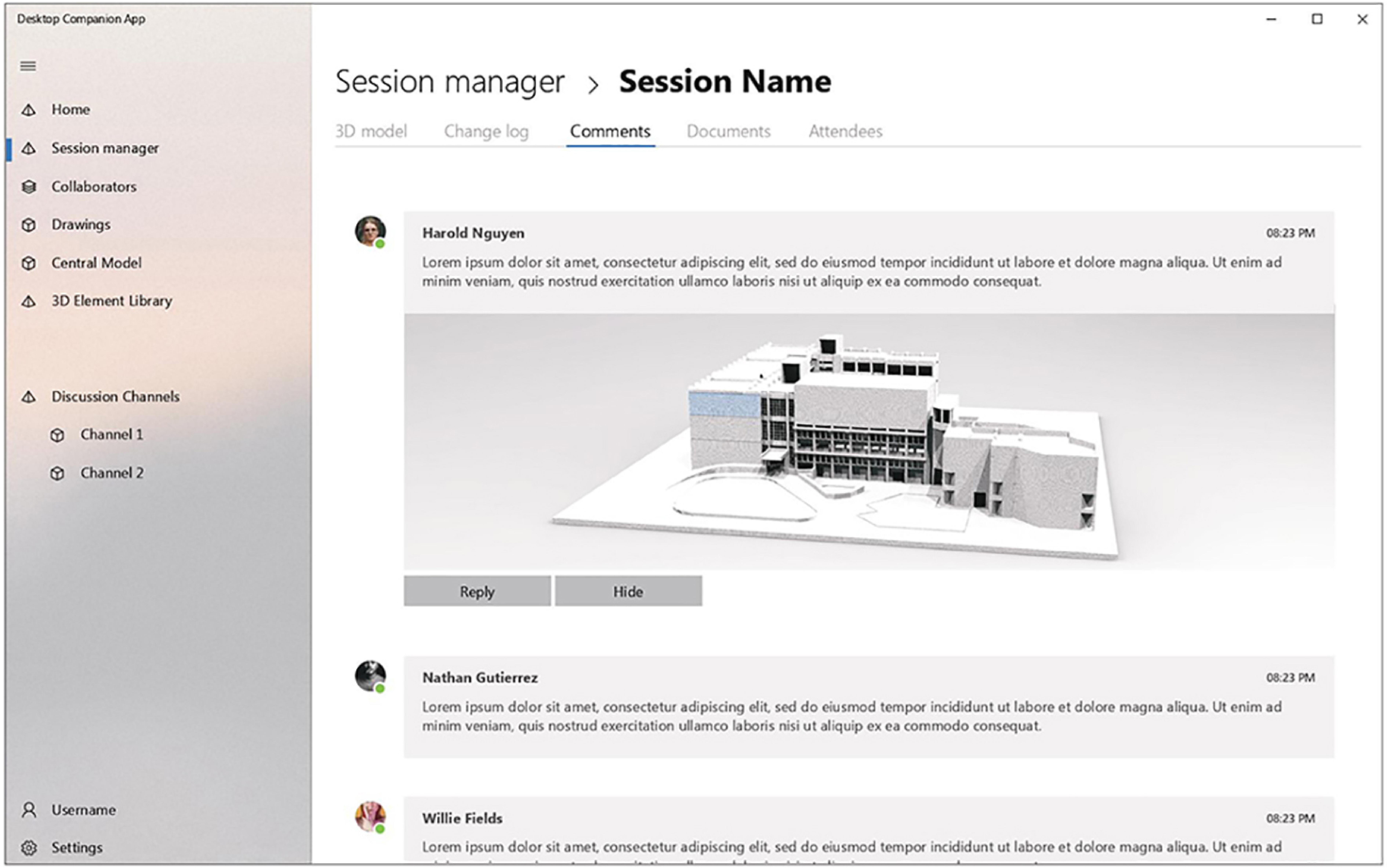


Fig. 7.16:

Hi-Fi Proto - Session X > Comments

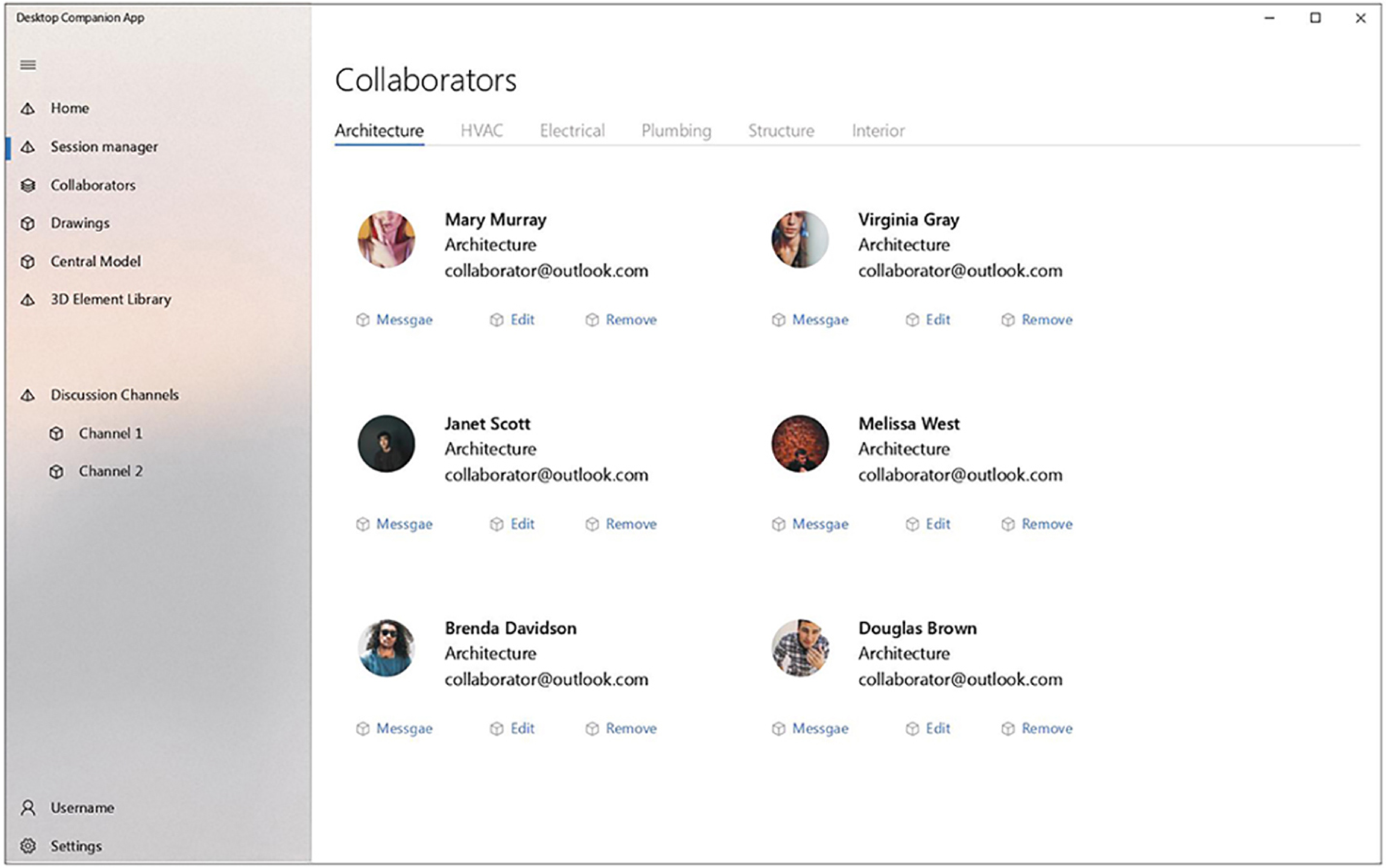


Fig. 7.17:

DCA Hi-Fi Proto - Collaborators

8 Usability Evaluation

Mixed reality systems provide a unique user interface known as a spatial interface, which exists in 3-dimensional physical space rather than a 2-dimensional screen. Since mixed reality is a formative technology, no formal usability guidelines are present for designing or evaluating MR based experience and spatial interfaces.[22]

Existing evaluation methods designed for evaluating traditional 2D interfaces are not directly applicable to mixed reality because of distinctive characteristics of spatial interfaces. A study identified several issues faced due to the physical environment and problems faced by the evaluator and the user while performing different types of usability evaluations on a mixed reality system.[21]

8.1 Usability Method

For evaluating and validating our design, we are using a formative evaluation method. Formative evaluation is an observational method which is used to assess user-interactions by placing the subjects/ users in a task-based scenario. This method can give us quantitative (like task timings, errors, etc.) as well as qualitative (like user feedback, reactions, comments, etc.) data. We seek primarily for qualitative analysis of the spatial interface of our platform.

Our formative evaluation will take the following path

1. Developing user task scenarios
2. Inviting two or three users at a time for accomplishing given tasks
3. Collecting quantitative data while the users perform different tasks
4. Gathering quantitative feedback

User Task Scenarios

The user tasks are developed for engaging multiple users in a given activity. Users would command each other for performing several actions and attain a common goal at the end.

Following are the developed user task scenarios
1. Adding an element to an existing model
User A would ask user B to add a partition wall at a specific location in a given space (3D model of a room). This task will include communicating the intent of user A to user B and collaboratively placing the required element at the desired place.

2. Manipulating an element (moving & rotating)
User B would place an annotation in the model for changing the position and rotation of existing furniture in the 3D model of the room. User A will have to act on the given annotation. The user B will guide user A to achieve the desired goal.

3. Using tools like section planes and layer toggle
Both the users would be asked to find a particular object collaboratively in a given 3D model of the building (IDC 3D model). The object would be at any random unknown location inside the building. Users have to use layer toggle or section plane tools to find the object.

8.2 Data collection and measurement methods

The types of methods would be used for data collection.

1. NASA Time Load Index

NASA TLX is a 20 point scale which is used to measure 6 parameters

- **Mental Demand:** How mentally demanding was the task?

• **Physical Demand:** How physically demanding was the task?

• **Temporal Demand:** How hurried or rushed was the pace of the task?

• **Performance:** How successful were you in accomplishing what you were asked to do?

• **Effort:** How hard did you have to work to accomplish your level of performance?

• **Frustration:** How insecure, discouraged, irritated, stressed, and annoyed were you?

By incorporating a multi-dimensional rating procedure, NASA TLX derives an overall workload score based on a weighted average of ratings on six subscales.

2. Usability questionnaire
A usability based questionnaire specific to each task executed by the users would be asked and analyzed.

8.3 Observations

The prototype was tested with practicing Architects and few observations were made which are as follows

1. There is a learning curve involved for using Hololens which hinders the experience of the application being tested. The users should be used to the Hololens gestures prior to the Application testing.

2. Voice instructions helped in on-boarding the user to the application.

3. Users were able to perform activities easily once they got used to Hololens gestures.

4. Gaze line helped user to be aware of where other collaborators are focusing in realtime.

5. Technology adaptability might be an issue with aged users as they prefer conventional methods for practicing design.

6. People find the system helpful as if also allows them to work without travelling.

7. Layer UI panel blocks they view of he 3D structure when layers are toggled, causing confusion. User needs active feedback on interactions when UI is spatial.

8. Users got confused between what has been designed for the project or what Hololens already presents.

User Statements

1. Such a project can help architects to quickly iterate on building massing or structure design using primitive shapes and pre-defined elements in the initial stages.

2. The product can be used in later stages of the project where the 3D models are ready.

3. Ability to place the model on a real table if in case an open are is not available.

4. Changes made on the scaled model should be replicated on true scale model as well.

The data was collected using NASA TLX and time based activity analysis was done, but due to lack of experience in using Hololens the users were not able to focus and perform the tasks. In order to evaluate such projects with such devices the users should be well versed with the gestures and device system. Also, these kind of products are not yet present in the market, the comparison with existing products don’t make sense.

9 Conclusion

In this project we designed an ecosystem on a mixed reality platform for enhancing the collaborative working between the stakeholders. The ecosystem includes a mixed reality collaborative platform developed for Microsoft HoloLens (working prototype) and a Desktop Companion Application designed using UWP (Universal windows Platform) guidelines. A cloud server was also developed which handles the remote and local collaboration, data exchange between the collaborators and also data exchange between the HoloLens and Desktop Companion Application.

The project included thorough study and understanding of CSCW systems, based on which our ecosystem stands. We also closely studied the collaborative practices and exchange of data between AEC industry professionals during the projects.

A crucial part of the project was to design for spatial computing and interfaces. The project investigated new interaction methods and activities to be perform in mixed reality for seamless collaboration experience. Based on the location of the user, we identified several scenarios which were designed based on the study and requirement from the context and prototyped on HoloLens. The system as of now is on final stages of development and we intend to test and evaluate our platform with actual stakeholders by the given evaluation method in previous section.

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