humantech

D4.4 – BIMxD XR visualization prototype

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Disclaimer

Acronyms and definitions

Acronym	Meaning
AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
BCF	BIM Collaboration Format
BIM	Building Information Modelling
BIMxD	BIM extended – Extended Dynamic BIM
bsDD	BuildingSMART Data Dictionary
CAD	Computer-Aided Design
CEN	Comate Européen de Normalisation - The European Committee for Standardization
DTLS	Datagram Transport Layer Security

GUI	Graphical User Interface
HTML	Hypertext Markup Language
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
MRTK	Mixed Reality Toolkit
PNG	Portable Network Graphics
QR	Quick-Response
REST	Representational State Transfer
RGB-D	Red, Green, Blue, Depth
SCTP	Secure Real-time Transport Protocol
SLAM	Simultaneous Localization and Mapping
SDK	Software Development Kit
SotA	State of the Art
UI	User Interface
WP	Work Package
VIO	Visual-Inertial Odometry
VR	Virtual Reality
WebRTC	Web Real-Time Communication
XR	Extended Reality – Augmented Reality + Virtual Reality

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Abstract

This document provides both an abstract and an executive overview of the Extended Reality (XR) prototype developed within Task T4.4 of the HumanTech project. The solution aims to improve on-site BIMxD visualization and operational support for construction workers through advanced wearable technology, particularly XR-glasses like the Microsoft HoloLens 2, and wearable cameras. By integrating these technologies into a unified system, the project enables real-time, high-quality, and localized BIMxD model visualizations on construction sites.

The intelligent system facilitates seamless hardware integration and employs sophisticated algorithms to calibrate wearable camera-based localization with local maps reconstructed by XR-glasses. This approach ensures that construction workers receive on-demand support through Augmented Reality (AR), enhancing their operational efficiency without disrupting their workflow.

The document provides detailed descriptions of the prototype's technical architecture, data flow, and integration process, offering insights into the hardware and software specifications required to implement this wearable technology. It also explains the methodology used for calibrating wearable camera-based localization with the local maps generated by XR-glasses.

Designed for a broad audience, including consortium members and the public, this report serves as a resource for both technical and end user partners. For technical partners, it outlines the system architecture and integration process, while for end users, it demonstrates how the solution will benefit construction workers by offering them on-demand, localized visualizations of BIMxD models in real-time.

In addition to presenting the motivation behind the design of this integrated wearable technology, the document emphasizes its practical applications within the HumanTech project, highlighting its potential to enhance on-site operational support and improve worker efficiency in construction environments.

The HumanTech project

The European construction industry faces three major challenges: increase the safety and wellbeing of its workforce, improve its productivity, and become greener, making efficient use of resources.

To address these challenges, HumanTech proposes to develop **human-centred cutting-edge technologies** such as wearables for workers' safety and support and robots that can harmoniously coexist with human workers while contributing to the ecological transition of the sector.

HumanTech aims to achieve major advances in cutting-edge technologies that will enable a safe, rewarding, and digital work environment for a new generation of highly skilled construction workers and engineers.

These advances will include:

- **Robotic devices equipped with vision and intelligence** that allow them to navigate autonomously and safely in highly unstructured environments, collaborate with humans and dynamically update a semantic digital twin of the construction site in which they are.
- **Smart, unobtrusive workers protection and support equipment**. From exoskeletons activated by body sensors for posture and strain to wearable cameras and XR glasses that provide real-time workers' location and guidance for them to perform their tasks efficiently and accurately.
- An entirely new breed of **Dynamic Semantic Digital Twins (DSDTs) of construction sites** that simulate in detail the current state of a construction site at the geometric and semantic level, based on an extended Building Information Modelling (BIM) formulation that contains all relevant structural and semantic dimensions (BIMxD). BIMxDs will act as a common reference for all human workers, engineers, and autonomous machines.

The **HumanTech consortium** is formed by 22 organisations — leading research institutes and universities, innovative hi-tech SMEs, and large enterprises, construction groups and a construction SME representative — from 10 countries, bringing expertise in 11 different disciplines. The consortium is led by the German Research Center for Artificial Intelligence's Augmented Vision department.

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1 Prototype Introduction

1.1 Background

XR technologies are fundamentally transforming the nature of work, training, and the effectiveness of actions, as well as our interaction with and perception of the world[1, 2]. These technologies have emerged as powerful tools for enhancing workflow, increasing worker efficiency, and improving safety and training practices[3]. The value of XR lies in its ability to augment users' perceptions of the real world by integrating digitally generated entities into their environment, thereby enriching their experience and interaction with their surroundings[4].

1.1.1 Wearable Technology Integration for Worker Support

The HumanTech project aims to revolutionize on-site construction worker support through the integration of advanced wearable technologies. This multi-purpose wearable solution is designed to enhance worker safety, optimize task performance, and improve the accuracy of construction processes by leveraging the latest developments in XR technologies and BIM frameworks.

Current wearable technology in the construction industry is largely focused on monitoring worker safety, such as tracking pose and motion to prevent injury. HumanTech advances this by integrating a combination of wearable devices that not only monitor worker well-being but also actively assist in physically demanding tasks. This includes the use of an inertial sensor network, and a miniature camera embedded in clothing, an exoskeleton to support strenuous activities, and XR-glasses for on-demand visualization. These innovations aim to minimize the physical strain on workers and reduce the risk of injury during tasks such as lifting heavy objects and to improve the workflow efficiency.

1.1.2 Localization and XR-Visualization on Demand

One of the critical challenges in XR technology is the need for precise localization to align virtual models with the real-world environment. Traditional XR devices, like the Microsoft HoloLens 2[5], have built-in localization capabilities but are often too bulky and obtrusive

[1] https://ieeexplore.ieee.org/document/8558774
[2] https://xbdev.net/misc_demos/demos/future-of-xr/paper.pdf
[3] https://xbdev.net/misc_demos/demos/future-of-xr/paper.pdf
[4] https://doi.org/10.1109/isar.2001.970521
[5] http://www.microsoft.com/de-de/hololens

for continuous use in construction settings. HumanTech addresses this by offloading the localization task to wearable camera based coarse localization through deep learning techniques. This is followed by a precise 6-degree-of-freedom alignment with the as-built digital twin model, enabling accurate and contextually relevant XR-visualizations.

The XR-glasses in the HumanTech framework are designed for on-demand use, calibrated to the worker's environment using landmarks observed by the wearable camera. This approach allows workers to access XR visualizations when needed without the burden of wearing the device continuously.

1.1.3 Overcoming Hardware Limitations with Remote Processing

Current self-sufficient mobile XR devices are limited in their capacity to effectively visualize complex models, typically handling only up to one million polygons. The constrained computing power and graphics capabilities of smartphones, tablets, and smart glasses present substantial barriers for both developers and users, limiting the performance and quality of immersive experiences. Overcoming these obstacles is essential to mainstreaming XR technologies and unlocking their full potential. The primary technological challenges in achieving high-quality XR experiences on mobile devices stem from the significant disparity in computing power between mobile hardware and modern PCs, particularly in terms of GPU and CPU capabilities. This gap hinders the ability of mobile devices to render complex 3D content and incorporate live-computed data into XR environments, leading to compromised visual quality and limited interactivity. Furthermore, the separation of application functionalities from 3D objects due to hardware limitations complicates the user experience and necessitates the adoption of remote rendering approaches. These challenges underscore the need for innovative solutions that can deliver rich, high-fidelity XR experiences without being constrained by the limitations of local hardware.

HumanTech overcomes this limitation by integrating the streaming technology (Hololight Stream[6]) from Holo-Light, which enables low-latency, remote rendering of highly detailed BIM models. Hololight Stream offloads the computational burden from local devices to powerful remote servers, allowing for the visualization of complex 3D objects and interactive content with minimal latency and without sacrificing detail. This solution ensures that workers can interact with data-intensive content in real-time, enhancing the accuracy and efficiency of their work[6].

1.1.4 System Integration, Data Management, and Privacy

The HumanTech system is designed with a strong emphasis on privacy and efficient data management. Because of the remote rendering process, data is not stored on the XR device but is streamed in real-time from the server, enhancing security by minimizing risks associated with device loss or unauthorized cyber-attacks. Additionally, this centralized management approach simplifies the enforcement of security protocols and standards, ensuring robust data protection throughout the application's operation.

To comply with GDPR regulations, the system ensures that no personal data, such as video or body pose information, is recorded or stored. All computer vision techniques are applied to single images, which are immediately discarded after processing. The closed-loop system between wearables and the edge device ensures that only geometric and semantic building information is stored, safeguarding worker privacy.

In training scenarios, where capturing workflows may be necessary, recordings will only be made with the explicit consent of the instructor, further emphasizing the system's commitment to privacy.

The HumanTech project represents a significant advancement in the integration of wearable technology and XR visualizations in construction. By addressing the limitations of current XR devices and ensuring robust data privacy, HumanTech provides a comprehensive framework that enhances worker support, improves task accuracy, and optimizes the use of materials on-site. The following sections will provide the technical overview of the prototype of the XR-glass integration and BIMxD visualization framework developed as part of the Task T4.4.

[6] https://hololight.com/products/hololight-stream-software-development-kit/

2 Prototype BIMSpace

2.1 Description

In the HumanTech project, a custom version of Holo-Light's Hololight Space AR/VR application, called BIMSpace (BIM Visualisation in AR Space), is developed for visualizing and interacting with high quality BIMxD models on the Microsoft HoloLens 2 on-site. The BIMSpace XR solution will utilise Hololight Stream SDK that will enable real-time streaming of AR/VR applications from powerful servers to mobile devices such as Microsoft HoloLens 2.

The BIMSpace solution will be able to load BIM-format IFC files natively and on-demand, visualise and interact with the BIM models in true scale, and read and write BCF (BIM Collaboration Format) files allowing for a seamless issue investigation. The BIMSpace solution will also be integrated with partner technologies such as Catenda Hub and BIMxD platform (developed within HumanTech by partner Catenda within WP2, refer to D2.3 – "BIMxD platform") and together will be deployed and validated in the HumanTech Pilot 1 use case 3 – "Detection of falling hazards" (related to T7.1 – "Digital Twin for material optimization and safety monitoring").

The BIMSpace XR solution is developed to achieve the HumanTech project scientific – technological objective (S&T2) of equipping the future generation of construction workers with lightweight, easy to carry and use, wearable XR glasses that can be used on-demand to visualise localised BIM information overlaying it onto existing building state for worker guidance and error prevention, leading to increased decision-making accuracy and improved worker training process.

2.2 Architecture & Data Flow

The BIMSpace XR solution is developed by customising Holo-Light's Hololight Space application and integrating it with the Hololight Stream SDK. The BIMSpace solution integrates with BIMxD platform and Catenda Hub to handle BIM data, including IFC files, BCF issues, and annotations, and enables immersive interaction within the real-world environment. Collectively, the solution is used for BIM visualization, issue management, and real-time collaboration.

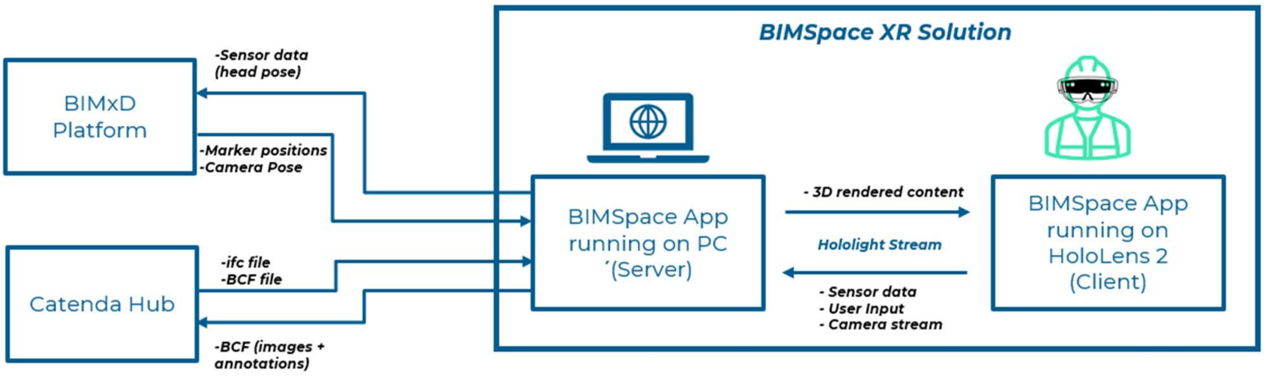


Figure 1 BIMSpace XR Solution - Architecture and Data flow.

The BIMSpace solution comprises of two components, a client application that functions on hardware such as the AR glasses (example: Microsoft HoloLens 2) and the server application hosting the AR application. The server application, built on Unity game engine[7], contains the necessary logic and functionalities for displaying holographic content in the XR device. This application runs on a server which can be a physical workstation, cloud environment, or virtual machine. The BIMSpace server application will receive data from Catenda Hub and BIMxD, remotely render the data on the server, and the entire server application will be streamed to the client AR device by leveraging Holo-Light's Hololight Stream plugin. Hololight Stream is a software development kit (SDK) that is used to securely stream the BIMSpace server application via WebRTC (Web Real-Time Communication) protocol to a designated client application that is installed on the AR glasses. The streaming technology enables the module to surpass the limitations of mobile devices like the AR glasses by shifting the rendering process from the low performance AR device to the high-performance server. Data will be securely streamed using Hololight Stream technology, ensuring no data is processed / stored on the mobile XR device and the data remains within the secure server infrastructure.

In the HumanTech project, the BIMSpace server application will fetch the BIM models (IFC file) and the related BCF files (JSON) from the Catenda Hub through REST APIs. The BIMSpace server application allows for an easy import of IFC files through a drag-and-drop feature. From the BIMxD platform, the server application will fetch marker positions

[7] http://www.unity.com/products/unity-engine

and camera pose. This data will aid in the localization and alignment of the virtual BIM model with the real environment on-site using markers for accurate spatial positioning.

The application logic of the BIMSpace server application enables the rendering of all the content on a powerful PC and streams the entire application to the BIMSpace client application. On the Microsoft HoloLens 2, the client application receives the application stream enabling the visualisation and interaction of 3D content on the HoloLens 2. In return, the client application sends the sensor data (SLAM data and head pose), user input and camera stream to the server application. This data exchange enables accurate visualisation and interaction of the BIM models along with BCF data. The server application allows for a user to write a BCF file and share it with Catenda Hub and shares the sensor data to the BIMxD.

The following sub-sections provide an overview of each of the components described in the Figure 1.

2.2.1 Hololight Stream

The Hololight Stream SDK is a remote rendering solution that enables real-time streaming of entire AR and VR applications. By streaming entire applications, Hololight Stream enables the visualization and interaction with highly polygonal, data-intensive content such as graphics-intensive 3D objects, 3D CAD models or BIM data which would otherwise be unlikely on native applications due to the limitation in the processing power of the XR devices.

The Hololight Stream SDK can be integrated into any Unity-based XR application. Its multi-device support and native Unity 3D integration streamline application development, saving time and effort while increasing the security and scalability of AR and VR applications. With Hololight Stream, user can run their Unity-built XR application on a powerful workstation, local server, or cloud-based infrastructure. It enables the secure streaming of AR/VR applications to all major AR/VR glasses and iOS devices in the market to visualize high fidelity content without down-sampling data.

Figure 2 showcases the experience of using Hololight Stream, wherein it enables visualisation of 3D objects with high number of polygons and complexity, giving a higher and improved level of visual detail and quality.

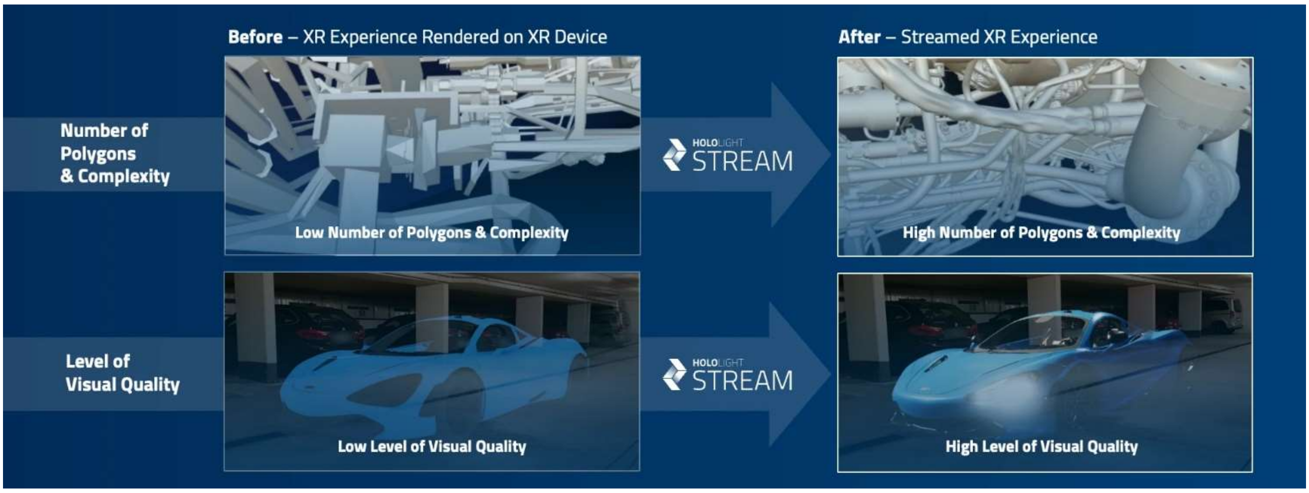


Figure 2 Before and After experience of using Hololight Stream.

2.2.1.1 *Functionality of Hololight Stream*

- Streaming data to AR/VR devices at its original complexity, size, and quality, eliminating the need for extensive data preparation.
- Secure streaming of XR applications over networks to control and protect critical and sensitive data by never storing it on endpoints.
- Creating and deploying a wide range of XR applications across multiple devices, increasing user engagement and delivering more dynamic experiences.
- Ensuring to efficiently render demanding and resource-intensive XR contents.
- Speeding up XR application development with a device-agnostic approach, native Unity 3D integration, and rapid application deployment.

2.2.1.2 *Requirements – Hardware, Development and Network*

Hololight Stream uses WebRTC protocol wherein data is transmitted securely with Secure Real-time Transport Protocol (SCTP) and Datagram Transport Layer Security (DTLS).

Hololight Stream needs to be installed on a Windows operating system, specifically, Windows 10 or 11. The machine should at least have a 16 GB RAM, while 64 GB is recommended for optimal performance. Hololight Stream does not use software rendering, rather hardware acceleration for creating AR frames. As a result, the processor requirement is not very high. However, it needs NVIDIA graphics processing unit (GPU) to function properly. The Graphics Processing Unit (GPU) should be at least an NVIDIA GTX 1070Ti for desktop systems. For optimal and improved performance, NVIDIA's RTX series graphics cards are recommended.

Table 1, Table 2 and Table 3 outline the hardware requirements, development environment requirements and the networking requirements of running Hololight Stream respectively.

Table 1 Hololight Stream - Hardware Requirements

	Minimum	Recommended
Operating System	Windows 10 (10.0..17763 Build) Windows 11 Windows Server 2019	Windows 10 (10.0..17763 Build) Windows 11 Windows Server 2019
Memory	16 GB	64 GB
CPU	Intel i5 8th Gen. 6 Cores AMD Ryzen 7 3700X	Intel i7 12 Gen. 12 Cores AMD Ryzen 9 3900X
GPU	NVIDIA GTX 1070Ti NVIDIA GRID for VMs	NVIDIA RTX 3080 TI NVIDIA GRID for VMs
Storage	SSD or NVMe	SSD or NVMe

Table 2 Hololight Stream - Development Environment Requirements

Component	Specifications
Visual Studio version	2019 2022
Visual Studio components	Universal Windows Platform; Game development with Unity; Game development with C++; Desktop Development with C++
Unity version	2021.3.x (minimum)
Unity components	Universal Platform Build Support; Windows Build Support IL2CPP

Unity Plugins	Pixyz
Mixed Reality Toolkit Version	2.8.2
Unity Editor Version	2022.3.13f1
Graphics card drivers	Latest NVIDIA GTX/RTX graphics card drivers

Table 3 Hololight Stream - Network Requirements

	Minimum	Recommended
Network	Wi-Fi 5Ghz	Wi-Fi 5Ghz
Bandwidth	20 Mbit	40 Mbit
Round Trip Time (Latecy)	-	Max. 50 ms
Notes: 1. The XR end-device must be capable of using STUN (Session Traversal Utilities for NAT) and TURN (Traversal Using Relay around NAT). 2. Enable incoming TCP Port 9999 and outgoing UDP Ports 16384-32768.		

2.2.2 Hololight Space

Hololight Space is the industrial AR and VR application for seamless visualization of high-polygonal 3D CAD/BIM data or enterprise digital twins. The application allows users to visualise and interact with complex 3D models in real-time within a shared virtual space. Through a high-performance streaming solution, Hololight Space application supports multi-user collaborative working environment enabling users to work together on the same model irrespective of the location. Common industrial use cases for Hololight Space in sectors like aerospace, automotive, construction, defense, mechanical engineering, and manufacturing include design review and rapid prototyping, factory planning and plant design, risk assessment and compliance checks, quality assurance and quality control, as well as product presentations and stakeholder engagement.

Key benefits of Hololight Space:

- Accelerate product development leading to faster time-to-market
- Efficient remote collaboration reducing travel and carbon footprint
- Economical and sustainable prototyping resulting in resource savings
- Quick and easy error detection

2.2.2.1 *Functionality*

Hololight Space functions include:

- Importing a variety of 3D CAD files.
- Space manager – enables managing files, navigating file hierarchy, and saving CAD files in one location.
- Tools menu – enables interacting with 3D models using a variety of tools such as cross-section, collision detection, x-ray, and annotation.
- Collaborative meetings – enable multi-user mode between AR & VR and invite stakeholders to meetings regardless of location.
- XR streaming – 3D content is streamed to end-devices in highest quality and original complexity without the need for data preparation
- Real world referencing – uses object tracking or QR codes as references or overlaying objects via object tracking by VisionLib[8].

2.2.2.2 *Requirements for Hololight Space – server and client*

Table 4 and Table 5 describe the minimum and recommended specifications for Hololight Space server application and Hololight Space client application respectively. The hardware requirements, development environment requirements and the networking requirements required are the same as for Hololight Stream, refer to section 2.2.1.2.

[8] www.visionlib.com

Table 4 Minimum and Recommended Specifications for Hololight Space (Server)

	Minimum Specifications	Recommended Specifications
Operating System	Windows 10 20H2 or above	Windows 10 20H2 or above
DirectX	Version 10 or above	Version 10 or above
Memory	8GB	16GB
Graphics Memory	4GB	6GB*
Graphics Card	Dedicated/Non on-board	NVIDIA RTX20xx or above
Processor	x86, Quad Core	x64 Quad Core or above

Table 5 Minimum and Recommended Specifications for Hololight Space (Client)

	Minimum Specifications	Recommended Specifications
Operating System	Windows 10 version 17763.0 or higher	Windows 10 version 17763.0 or higher
Architecture	ARM	ARM

Within HumanTech, the BIMSpace server application is developed in Unity game engine using C#. The Unity Editor version minimum requirement is 2021.3.x. In development, 2022.3.13f1 is used for being able to seamlessly use the latest version of Hololight stream SDK. WebRTC plugin was installed to develop outgoing video streaming from the HoloLens 2 device. As an AR application, the AR components used in the project are supported by Microsoft Mixed Reality Toolkit (MRTK). MRTK is also added to the development environment as a plugin. The required version of MRTK is 2.8.2. As the programming environment, Microsoft Visual Studio 2022 was chosen. The Hololight stream SDK is integrated into the Unity game engine, necessitating the use of the Unity editor. For the development of BIMSpace server application, Unity version 2022.3.13f1 was employed. Additionally, NVIDIA graphics card drivers and libraries were maintained up to date.

2.2.3 XR Device – Microsoft HoloLens 2

For HumanTech and specifically for T4.4, the Microsoft HoloLens 2 was chosen for the BIMSpace XR solution due to its advanced spatial mapping capabilities, intuitive hand-tracking, and seamless integration with BIM workflows. Its high-resolution mixed reality display allows for accurate visualization of 3D models and BIM data overlaid in the real world, while the built-in sensors and cameras enable precise alignment using markers like QR codes. Additionally, HoloLens 2 supports robust connectivity for remote processing and cloud integration, making it ideal for handling complex BIM models and facilitating real-time collaboration on-site. Its hands-free operation also enhances user interaction and productivity in construction environments.

In addition, HoloLens 2 can be integrated with a construction helmet, like the Trimble XR10, enhancing safety and usability on construction sites. This allows workers to comply with safety regulations while accessing XR features for real-time BIM visualization, clash detection, and progress tracking. The hands-free operation and rugged design make it ideal for field use, improving efficiency and accuracy in project execution while maintaining full protective gear.

Figure 3 Microsoft HoloLens 2[5]

Figure 4 Trimble XR10 helmet - The only HoloLens 2 solution compatible with an industry-standard hardhat [9] and certified for use in safety-controlled environments.

Within BIMSpace XR solution, the BIMSpace client application runs on the HoloLens 2. The client application receives the application stream from the server application by leveraging Holo-Light's streaming solution. It serves as the primary interface for users to visualize and interact with BIM models and annotations in a mixed reality environment.

2.2.4 Catenda Hub

Catenda Hub, explained in D2.3 – "BIMxD platform", is a common data environment (CDE) designed for managing construction and infrastructure projects. It is a BIM platform that provides storage, file management, and BCF handling, along with a 3D model viewer for IFC files and point clouds. It supports open standards like IFC, BCF, openCDE, and E57/LAS, and offers a web interface and API access. The platform includes a REST-based API for models, documents, and BCF, as well as a WebGL-based 2D/3D viewer that can be embedded. BIMxD utilizes Catenda Hub for data storage and uses its embedded viewer to display models and point clouds.

2.2.4.1 *Functionality*

Catenda Hub has the following functions[10]:

- Open standards-based cloud platform for construction and infrastructure projects

[9] Trimble Field Technology
[10] https://catenda.com/bim-solutions-open-standards/catenda-hub-common-data-environment/

- Centralizes all project data including 2D plans, 3D models, and documents
- Powerful 3D viewer with auto-generated 2D floor plans
- Issue management system for better coordination and collaboration
- Document management and storage capabilities
- Supports open formats like IFC and BCF for interoperability
- Mobile application (Catenda Site) for on-site project management
- User and project management tools for organizing team members and roles
- Visualization features including measurements, cuts, and object colouring
- Ability to link documents and data to models, creating a digital twin
- Accessible via web browser without need for specialized software

2.2.4.2 *Requirements*

The key technical requirements[11] of using Catenda Hub are:

1) Hardware recommendations:
    a) For regular projects (up to LOD 300):
        i) Processor: Intel Core i5 or equivalent
        ii) RAM: 8 to 16 GB
        iii) GPU: Integrated or 4GB dedicated
    b) For dense geometry projects (LOD 400 and above):
        i) Processor: Intel Core i7 or equivalent
        ii) RAM: 32GB
        iii) GPU: 8GB dedicated
2) Software requirements:
    a) Catenda Hub is accessed through a web browser, so no installation is needed
    b) Recommended browsers (by memory usage efficiency): Firefox, Chrome, Microsoft Edge.
3) Network requirements:
    a) Stable internet connection

[11] https://support.catenda.com/en/articles/6921941-hardware-recommendation

   b) Recommended download to upload ratio of 1:10 or above

Access requirements:

   c) Allow storage of data for hub.catenda.com during browser sessions
   d) Access to specific Catenda domains and ports must be enabled if using firewalls or proxies

4) Cookies:
   a) Browser must allow cookies for hub.catenda.com to remember login status and preferences

5) GPU usage:
   a) Ensure the system is using the dedicated GPU rather than integrated graphics for better performance

2.2.5 BIMxD platform

BIMxD platform developed by Catenda within WP2 is a platform that collects and processes the workflow and data of the Dynamic Semantic Digital Twins (DSDTs) of construction sites. It allows to capture and simulate in detail the current state of a construction site at geometric and semantic level, based on an extended BIM formulation encompassing all relevant structural and semantic dimensions. BIMxD platform is a cloud server, with functionality for data storage, processing, and viewing. It attempts to distribute common relevant data between the many partners, to make concrete common ground in different tasks in HumanTech, to process data, and to show the results.

BIMxD platform has been described in detail in a dedicated deliverable, D2.3 – "BIMxD platform".

2.2.5.1 *Functionality*

BIMxD platform is the digital twin backend in HumanTech. It is a server-based solution that offers storage and content handling functionality together with connected model server (Catenda Hub) and it also has a rich set of API endpoints and web pages for a set of different use cases in HumanTech. These are easily extensible since the server is developed with Python and FastAPI. The set of endpoints and web application pages are described in D2.3 – "BIMxD platform".

2.2.5.2 *Requirements*

The BIMxD backend is the core for a lot of functionality in HumanTech. It is easy to add new endpoints to connect new external or internal functions/programs if running on the same server.

The server currently runs on Amazon Web Services (AWS) in Ireland. It is an Ubuntu Linux server using AMD x64 instructions. Hardware requirements depend on performance needs, but currently it has 16 GB ram. In the scenario of heavy point cloud calculations, more RAM would have to be added.

2.3 BIMSpace Features

2.3.1 BIM Visualization

This section outlines the functionality of BIMSpace solution that allows users to load Industry Foundation Classes (IFC) files and visualize the corresponding Building Information Modelling (BIM) models overlaid on the real-world environment. This feature enhances the interaction between digital 3D models and the physical site, providing users with a powerful tool for design review, decision-making and coordination.

2.3.1.1 *Loading IFC file*

The BIMSpace server application supports the loading of IFC files, a widely used open standard for BIM data exchange developed by buildingSMART International. BIM and IFC have been thoroughly defined and explained in previous HumanTech deliverables: D1.2 – "HT architecture definitions (initial)"; D2.1 – "BIMxD IDM with classes and attributes according to ISO 29481 and respective standards"; D2.2 – "Open-source BIM authoring tools" and D2.3 – "BIMxD platform".

The process involves:

1. File Download: Users can download the latest and updated IFC file from Catenda Hub and store it on the local machine.
2. File Import: Users can import IFC files into the BIMSpace server application through a simple interface with a drag-and-drop feature, where the file is parsed, and the BIM data is extracted.
3. Data Processing: The application processes the IFC data to reconstruct the 3D BIM model, including all geometry, spatial relationships, and metadata associated with building elements.

For HumanTech, Holo-Light in collaboration with partner RPTU developed a BIM model of Holo-Light's office space for testing and validation. The complete functionality of BIMSpace XR solution was tested and demonstrated on this IFC file (see Figure 5). The BIM model of the office space was utilized as the test environment; however, for the pilot demonstration, specifically Pilot 1, the XR solution will be tested with more complex models at the pilot site.

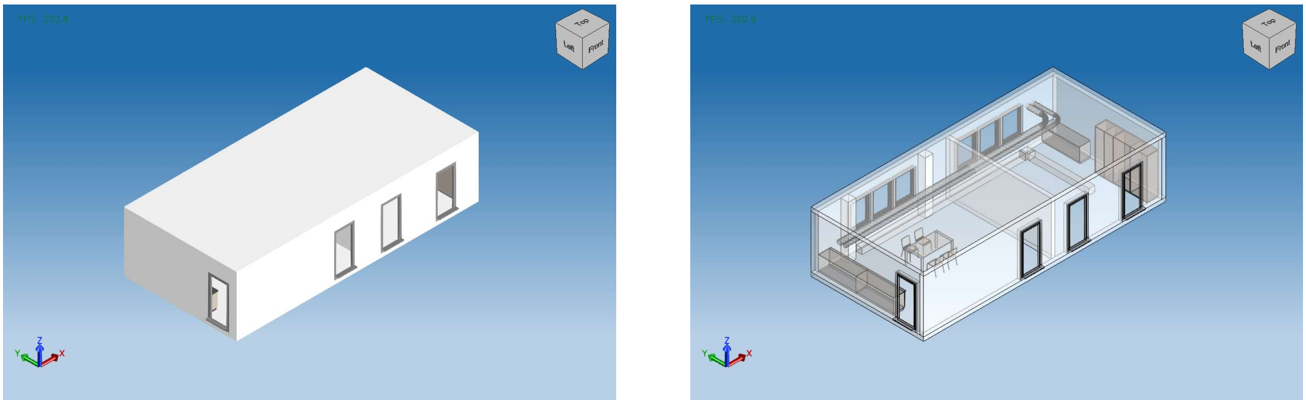


Figure 5 The BIM model (IFC file) of Holo-Light's office space developed in collaboration with RPTU. This model was used for demonstrating the features and functionality of BIMSpace XR solution.

2.3.1.2 ***Visualizing the localised BIM model***

Once the IFC file is loaded into the BIMSpace server application on the PC, the XR application enables users to visualize the BIM model overlaid on the real-world environment on the BIMSpace client application on the HoloLens 2. The BIM model is remotely rendered on the PC and streamed to the HoloLens 2 XR device. This is achieved through the following steps:

1. Model Localization: The BIMSpace client application aligns the BIM model with the physical environment using markers ensuring that the digital model accurately aligns and corresponds to the real-world site. The client application enables the user to scan a visual marker like a QR code, which stores the coordinates of the physical environment. After scanning the marker, the client application aligns HoloLens 2's reference system with the BIM reference system. Section 2.3.4 describes in depth the localisation and alignment process using markers.
2. Real-World Overlay: The localized BIM model is rendered in the XR environment, allowing users to see the virtual building elements of the BIM model superimposed over the actual surroundings. This overlay is interactive, allowing

users to explore the model from different angles and perspectives within the context of the real site.

Figure 6 showcases the BIM visualization of the Holo-Light office space as viewed on the HoloLens 2.

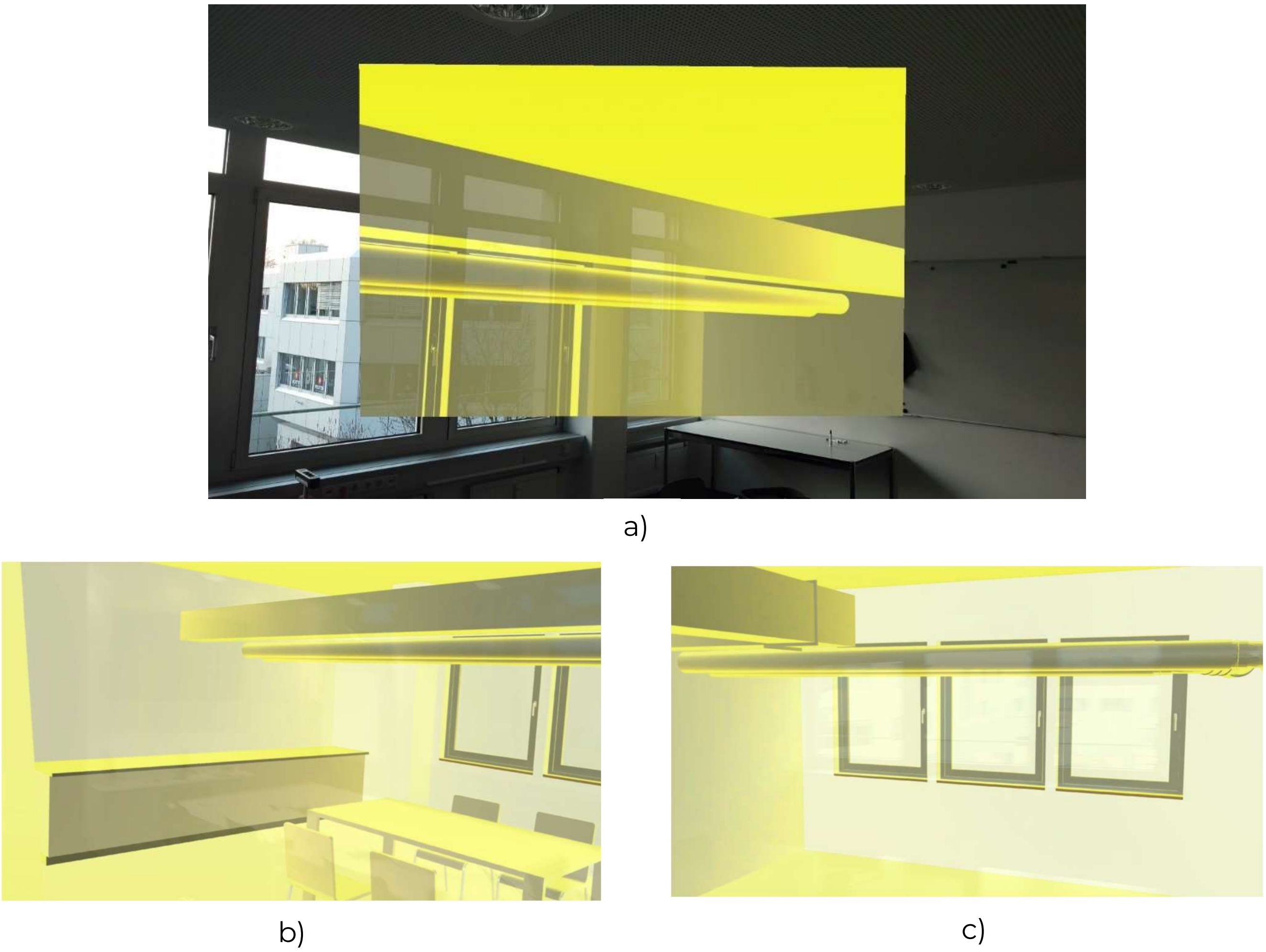


Figure 6 a) The BIM Model of Holo-Light office space as visualised on a HoloLens 2 and overlaid on the real environment; b) and c) are visual representations of the BIM model as visualised on the HoloLens 2.

2.3.2 BCF Issue Investigation

The BIM Collaboration Format (BCF) is an open standard designed to facilitate issue tracking and communication in BIM projects. It allows different software tools to share information about issues related to the BIM model, including their location, status, and associated metadata. BCF has been defined and explained in deliverables D1.2 – "HT architecture definitions (initial)" and D2.3 – "BIMxD platform".

One of the core functionalities of the BIMSpace solution is the ability to read and write BCF files facilitating easy visualisation, interaction of BIM issues in an XR environment enhancing decision making and issue management processes in the HumanTech project.

2.3.2.1 *Reading BCF files*

The BIMSpace server application fetches BCF files from Catenda Hub via REST APIs to visualize BIM issues directly within the XR environment. This process involves parsing the BCF data to extract relevant information such as viewpoints (as PNG mages), comments, and issue statuses. These elements are then rendered in the XR environment, allowing users to interact with and navigate through the issues in a fully immersive 3D space.

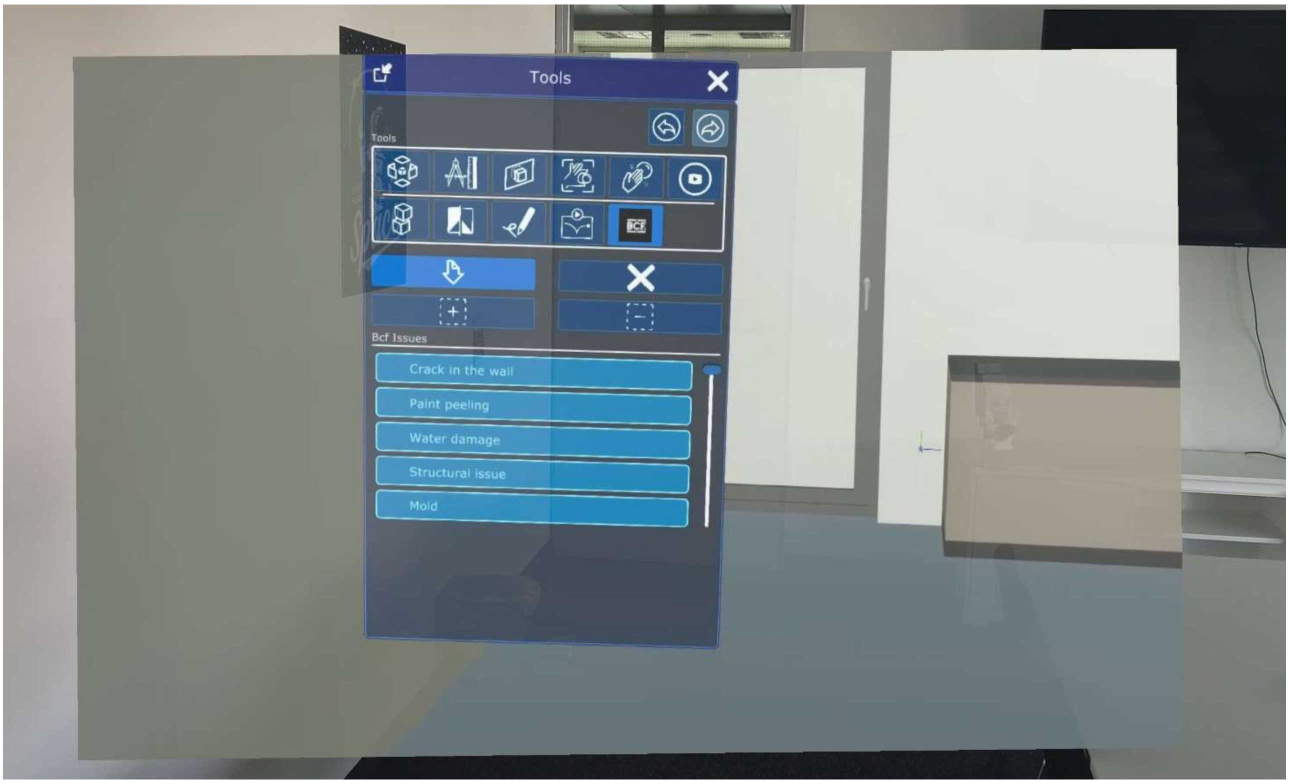


Figure 7: BIMSpace Server Application - BCF Panel

A user-friendly graphical user interface (GUI) panel designed specifically for handling BCF issues has been developed, as shown in Figure 7.

The GUI panel will allow users to efficiently retrieve BCF issues as JSON files stored in Catenda Hub through its robust REST-based BCF API. This ensures that the most up-to-date issue data, such as design conflicts, task assignments, or problem areas, is pulled directly into the XR environment and visualised on the BIMSpace client application on the HoloLens 2. Once the BCF data is retrieved, the BCF panel showcases all the BCF issues within the BIM project as a list of issues as detailed in Figure 8. The BCF panel includes intuitive functional buttons that streamline the selection and deselection of issues, allowing users to efficiently manage and navigate through BCF data with ease. These controls enhance user interaction by enabling quick filtering, toggling, and focus on specific issues, ensuring a smoother and more efficient workflow within the XR environment (see Figure 8).

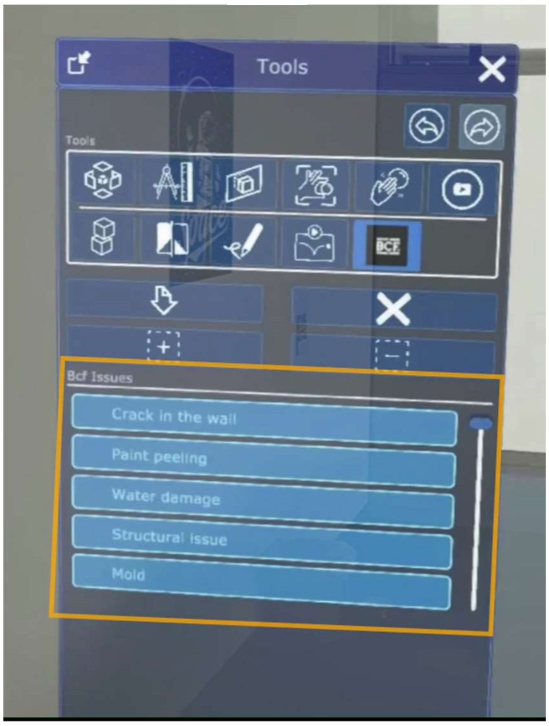
Functional buttons of BCF Panel include:

1) Download BCF – fetches all the BCF issues within the BIM project and adds them to the list.
2) Select One BCF – allows user to select a particular object/building element in the virtual BIM model in the XR environment to view the associated BCF issue.
3) Remove All BCF – allows user to deselect all the highlighted BCF issues in the XR environment.
4) Deselect One BCF – allows user to deselect the highlighted BCF issue of a particular object/building element in the virtual BIM model.

The visual representation of these buttons have been showcased in the figures, Figure 9, Figure 10, Figure 11, and Figure 12 respectively.

a)

b)



c)

Figure 8 BCF Pane - a) BCF Functionality embedded with BIMSpace application tools; b) Buttons to download BCF files from Catenda Hub, Deselect All BCF issues, Select/Deselect an object to view the object's BCF issue; c) A scrollable list of BCF issues within a BIM project

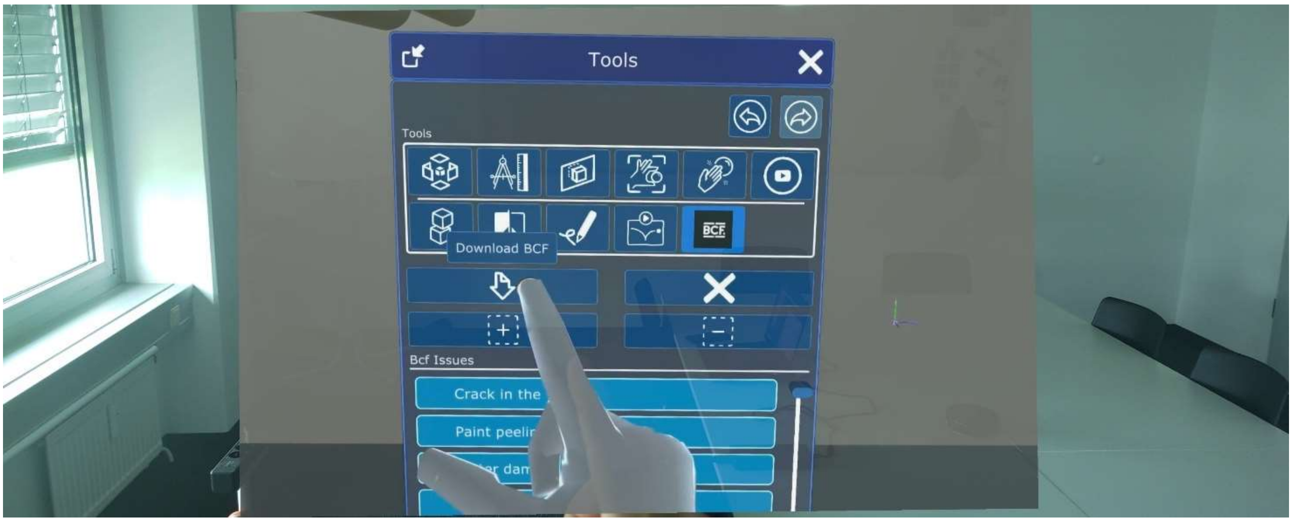


Figure 9 Download BCF – fetches all the BCF issues within the BIM project and adds them to the list.

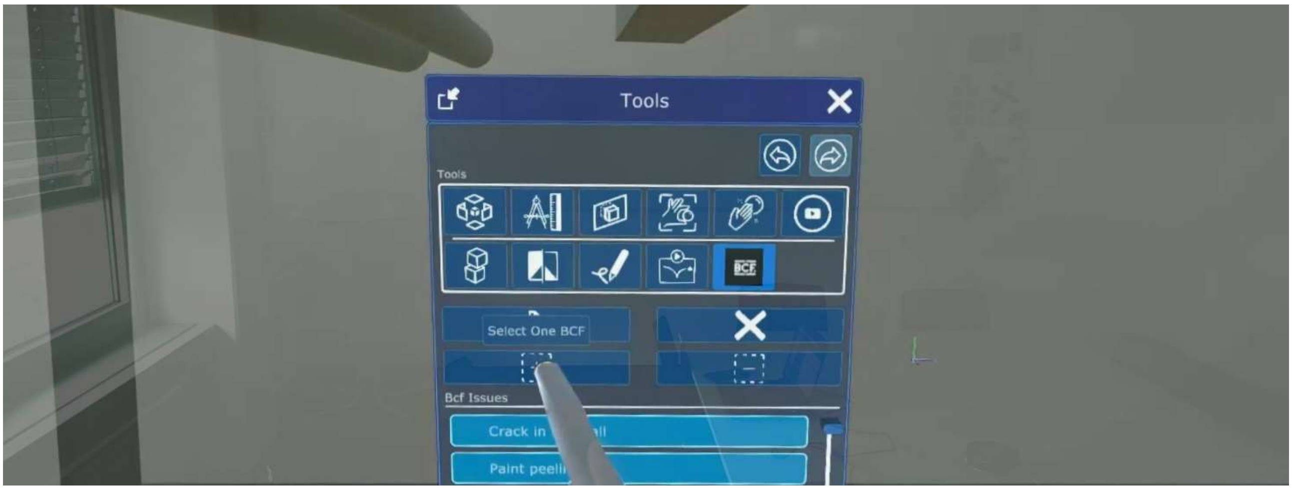


Figure 10 Select One BCF – allows user to select a particular object/building element in the virtual BIM model in the XR environment to view the associated BCF issue.

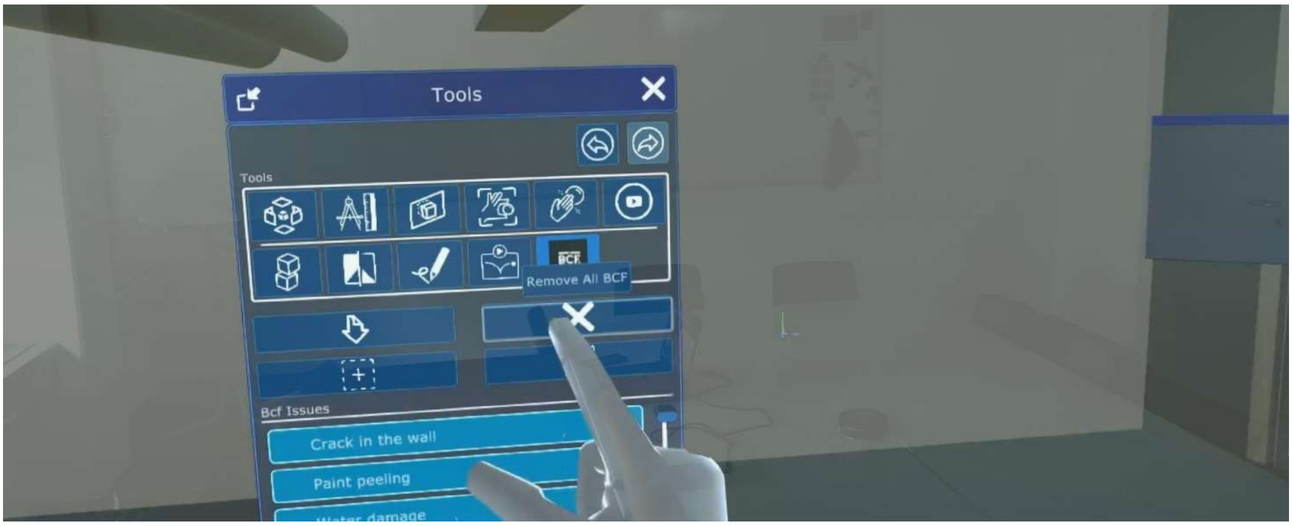


Figure 11 Remove All BCF - allows user to deselect all the highlighted BCF issues in the XR environment.

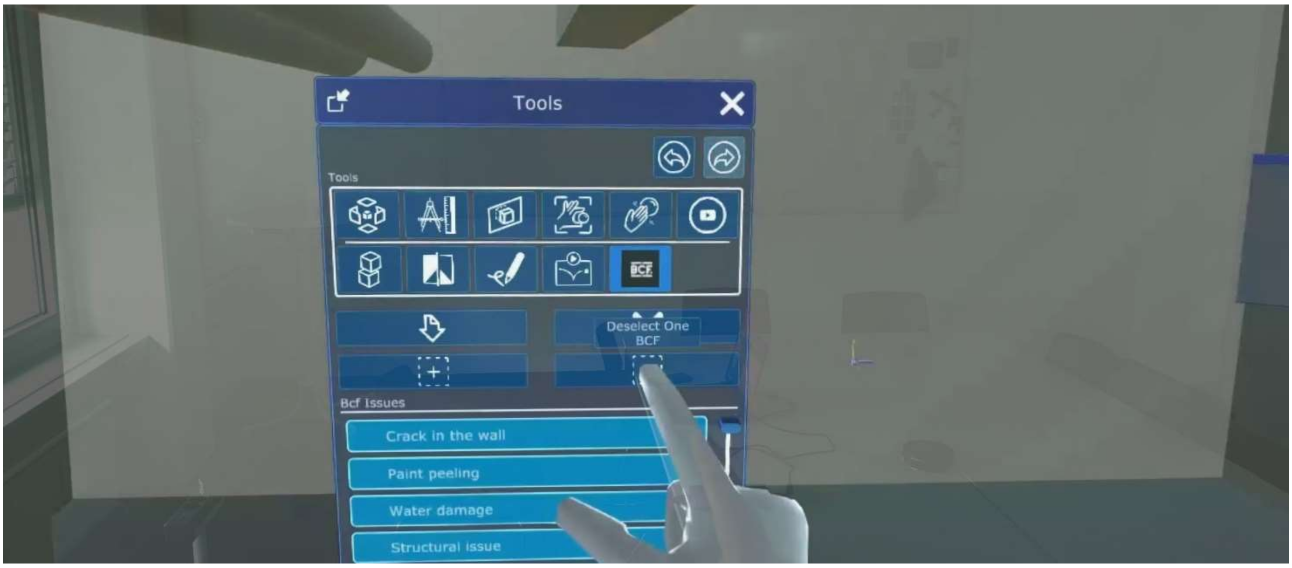


Figure 12 Deselect One BCF – allows user to deselect the highlighted BCF issue of a particular object/building element in the virtual BIM model.

The BIMSpace server application links each BCF issue to its corresponding object within the IFC model. This linkage enables users to visualize and interact with the model and associated issues in an immersive 3D space, significantly improving collaboration and decision-making processes. For testing and validation, sample BCF files (JSONs) were created for the Holo-Light's office space IFC file. Figure 13 showcases a sample BCF issue linked to a wall with a tooltip connection.

As shown in Figure 13 and Figure 14, for each issue linked to an object, the XR application will automatically create an interactive tooltip that provides a detailed summary of the issue. The tooltip will display important metadata such as the issue description, assignee, and resolution status. Additionally, the affected object in the IFC model will be visually highlighted to ensure that the user can easily identify it within the complex BIM environment. This feature helps users quickly assess and prioritize issues based on their spatial and visual context within the model.

To enhance usability, the system leverages the HoloLens 2's advanced mixed reality capabilities, enabling users to interact with the highlighted objects and tooltips in a hands-free, intuitive manner. Users can directly engage with the BCF issues by navigating the 3D space, inspecting objects, and adding annotations or resolving issues on-site. The tooltips and highlighted objects ensure that issue identification and resolution are seamless, contributing to a more efficient issue-tracking workflow.

Additionally, the BIMSpace XR solution allows for the simultaneous visualization and interaction with multiple BCF issues within the immersive environment as shown in

Figure 15. Users can view, manage, and address several issues at once, enabling more efficient issue tracking and resolution across the BIM model, thereby enhancing productivity and collaboration in real-time.

The immersive nature of XR enables users to inspect the building model from various perspectives, providing a more intuitive understanding of the issues at hand. This enhanced visualization supports more effective decision-making as users can better grasp the spatial context of the issues and collaborate with team members in real-time.

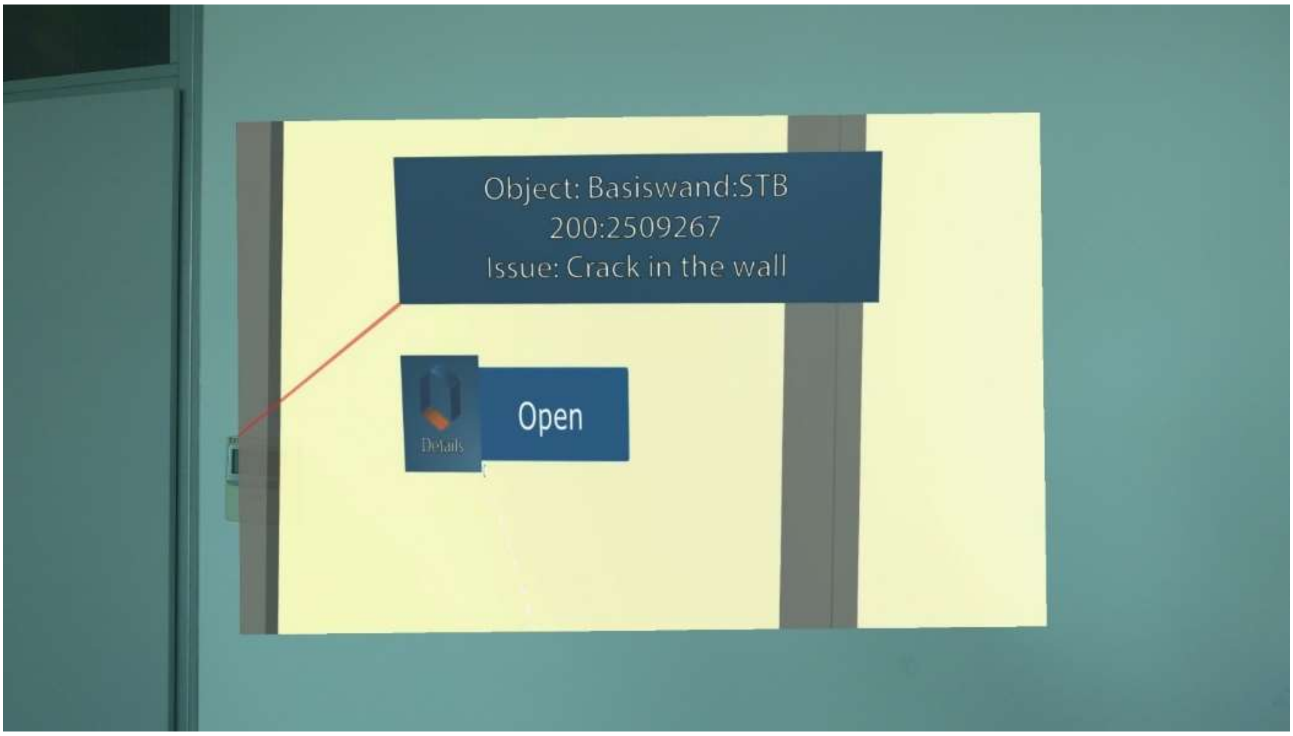


Figure 13 Visualisation of a BCF issue linked to the wall object on the Microsoft HoloLens 2.

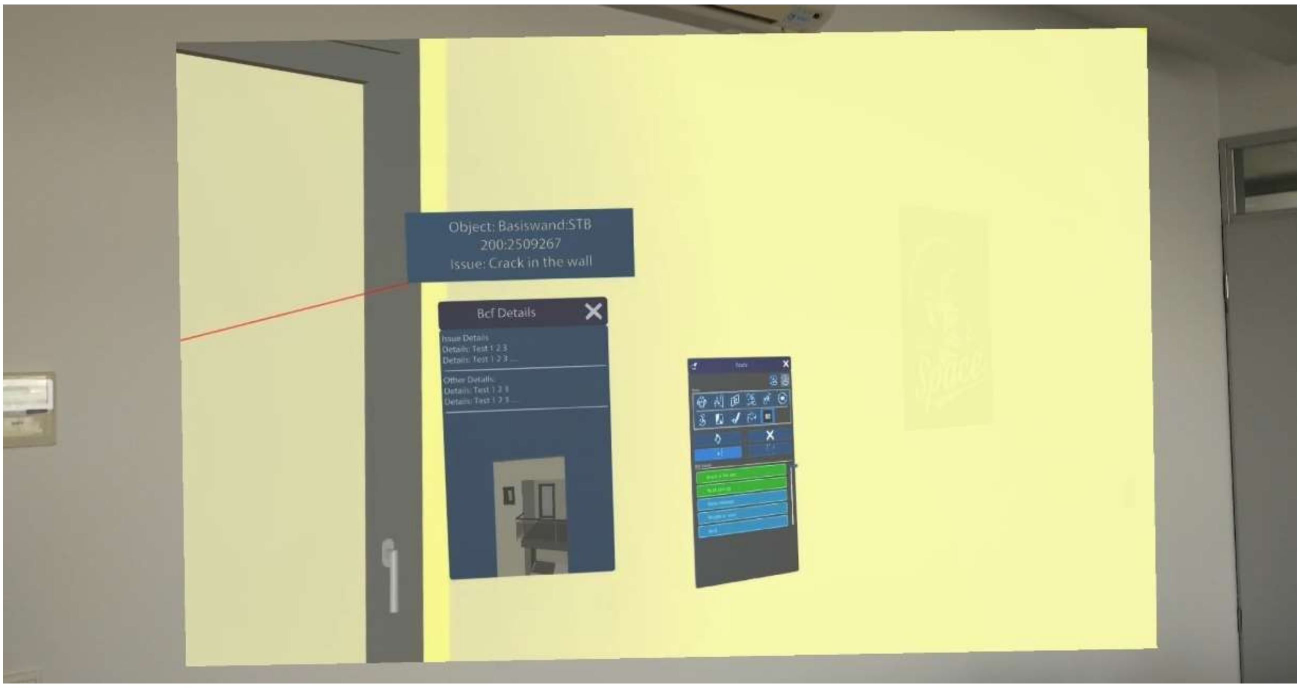


Figure 14 Visualisation of a detailed BCF issue - images, issue description. A sample BCF issue was created for the purpose of testing.

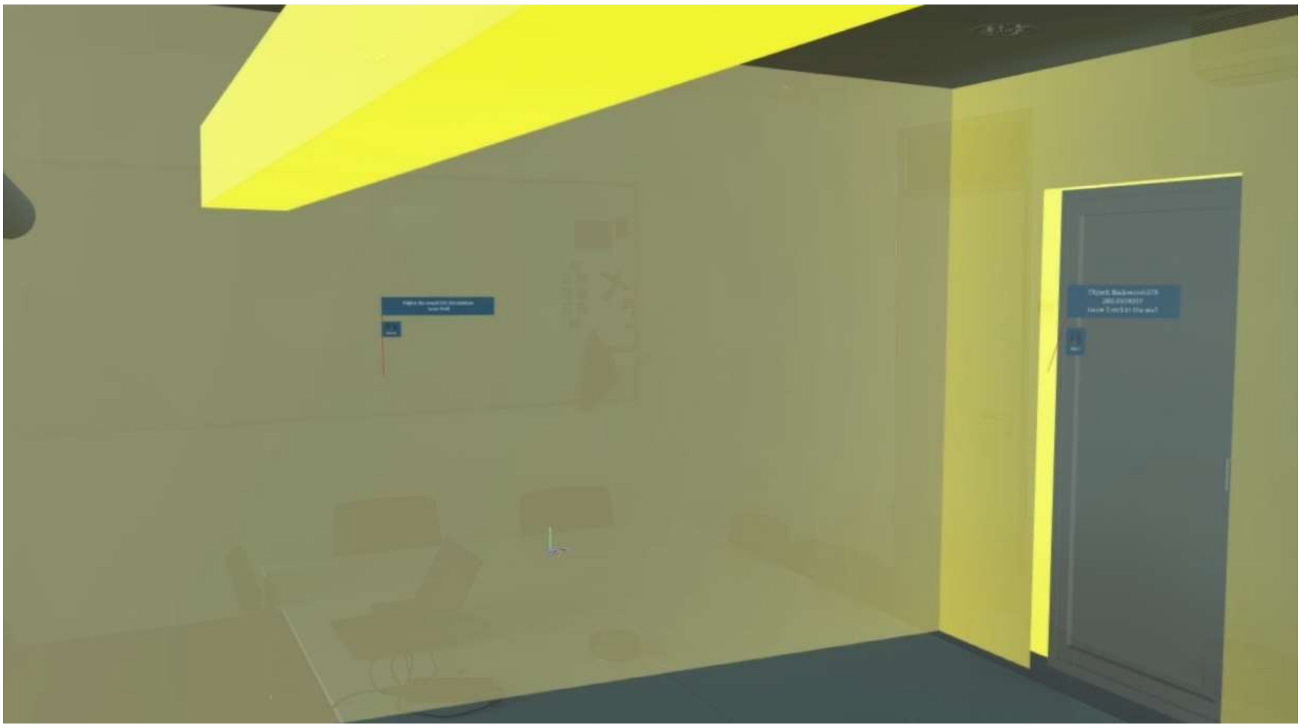


Figure 15 Visualisation of multiple BCF issues in the XR environment as seen on a Microsoft HoloLens 2.

2.3.2.2 *Writing BCF files*

The XR app not only allows users to retrieve and view BCF issues but also provides functionality to create, edit, and submit new BCF files directly from within the XR environment to the Catenda Hub servers.

Within the XR environment, users can create new BCF issues by selecting objects in the BIM model on the BIMSpace client application and generating issue reports. This process involves identifying the object/IFC element of concern, annotating the issue, and providing relevant information such as issue description, priority, and assigned responsibility along with the function to attach an image taken from the HoloLens 2 front camera. Users can also add visual annotations in 3D space, such as highlighting objects, adding shapes, or text, which are then linked to the corresponding issue. These visual markers enhance clarity and communication within the team. The app also allows users to review and edit previously created/fetched BCF files before submission. Users can update issue statuses, add comments, and create new viewpoints (as PNG images) directly within the application. The BIMSpace server app automatically compiles these details into a structured BCF file format (JSON), ensuring compatibility with industry standards and other BIM tools.

After creating or editing a BCF issue, the user can submit the file to the Catenda Hub server using the app's API integration. This ensures that all changes are captured and stored in the BIM project and the issue is synced with the cloud-based collaboration platform, allowing other project stakeholders to access, review, and resolve the issue from their respective tools. The seamless integration with the Catenda Hub server ensures real-time updates and efficient communication across teams.

This feature is under-development at the time of the submission of this deliverable and will be showcased in Pilot 1 use case 3 under WP7.

2.3.3 BIM Annotation and Review

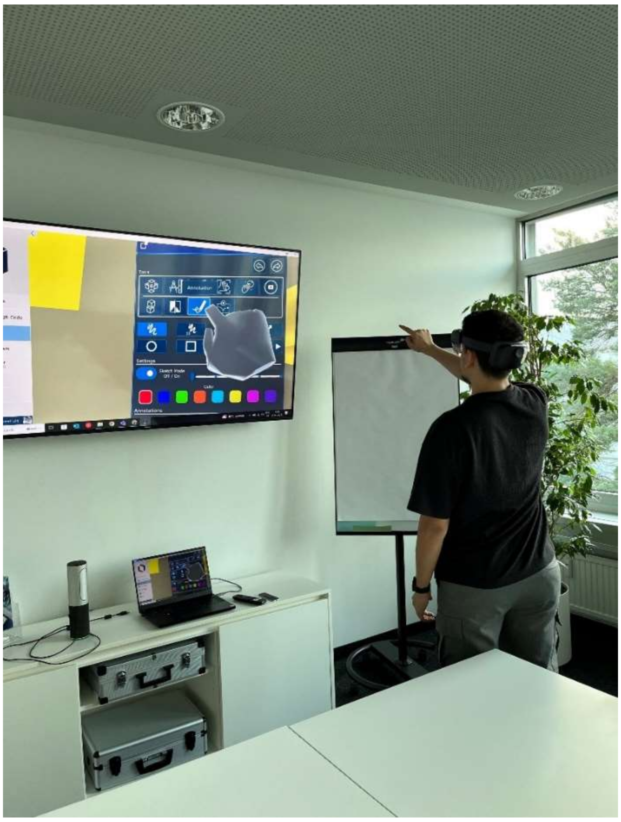
The BIMSpace XR solution, specifically the client application on the HoloLens 2, allows users to annotate and review IFC objects within a BIM project in an immersive XR environment. The application supports a variety of annotation tools, enabling users to communicate design intentions and issues more effectively.

The XR application is equipped with a suite of annotation tools (refer to Figure 16) that provide users with the ability to markup BIM elements directly within the 3D environment.

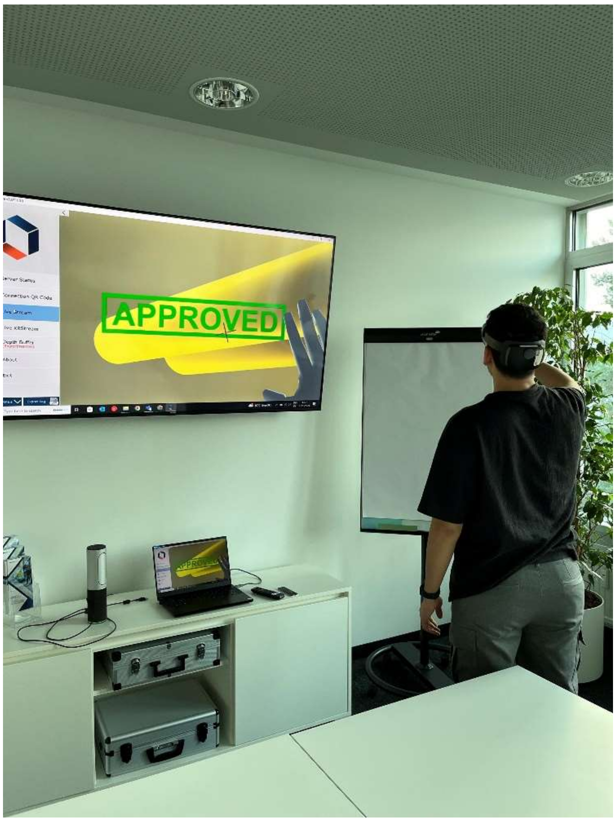
Tools include:

- 2D and 3D Text Annotations
- 2D and 3D Drawing
- Adding Shapes
- Stencils – approval, revision, or request for information

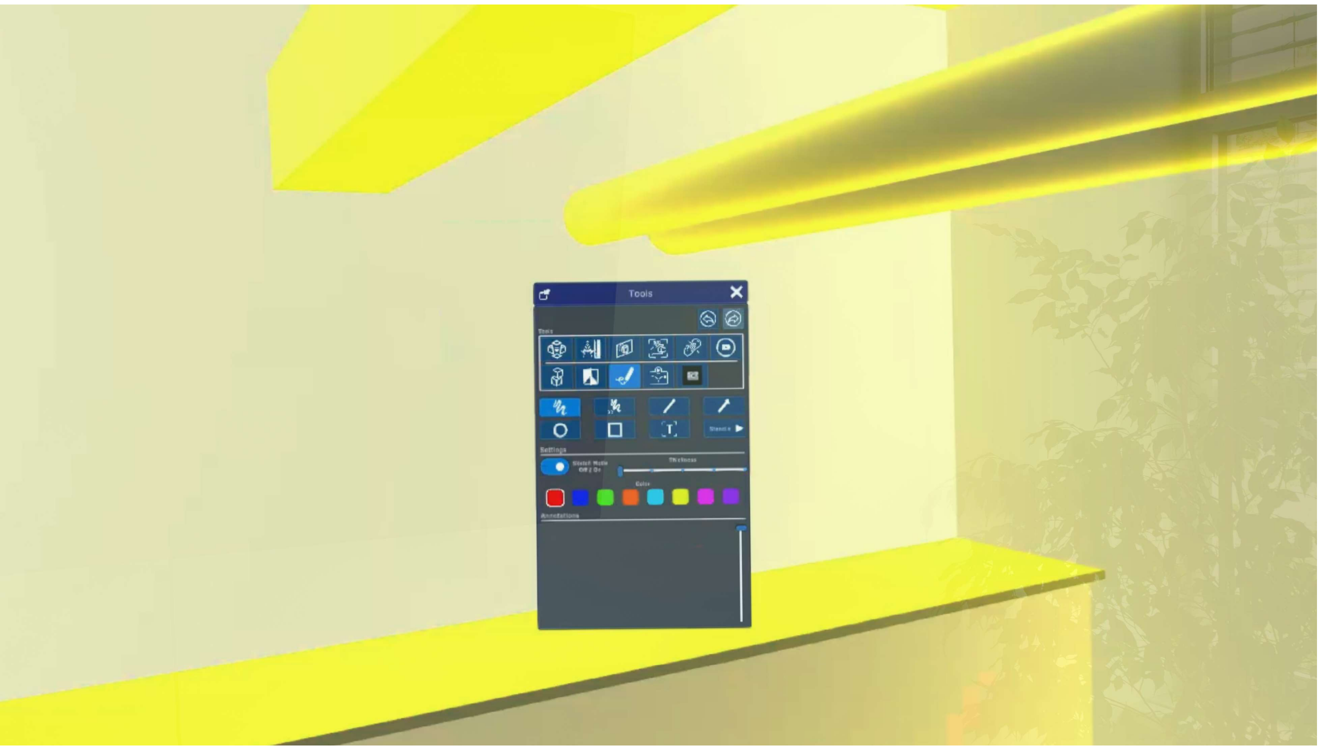
These annotation tools in the XR application enhance BIM review by providing intuitive, visual methods for communicating and analysing design details directly within the 3D model. By enabling users to add 2D/3D text, stamps, colours, and shapes, the tools make it easier to highlight specific areas of interest, mark issues, and convey feedback clearly and consistently. This visual clarity fosters better understanding among stakeholders, reduces misinterpretations, and accelerates decision-making. Additionally, real-time interaction with these annotations within the immersive XR environment enhances collaboration, ensuring that all participants are aligned on the design intent and necessary actions, ultimately leading to more accurate and efficient project execution.



a)



b)



c)

Figure 16 BIM Annotation: a) The user can annotate and markup the BIM elements in the XR environment; b) The user can use preloaded stencils ('Approved', 'Not Approved' etc) to annotate the BIM elements; c) The 'Tools' menu includes a suite of annotation tools such as 2D/3D drawing, text, shapes and stencils.

2.3.4 Alignment and Localization of BIM Models in XR

Alignment and localization refer to the process of correctly positioning a virtual BIM model within the real-world environment in XR applications. Alignment ensures that the digital model's geometry matches the physical site in terms of scale, orientation, and position. Localization involves accurately determining the spatial coordinates of the virtual model relative to the user's location and the surrounding physical space.

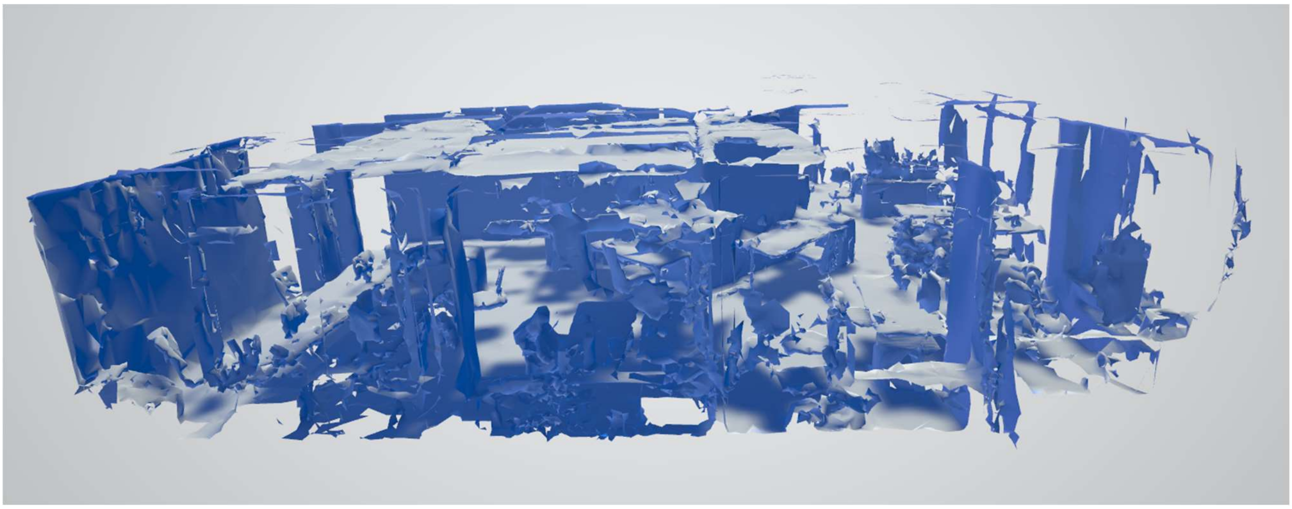
Accurate alignment and localization of the BIM model in a XR environment are essential for ensuring that the virtual model overlays precisely onto the physical site, enabling realistic visualization and interaction. This spatial accuracy enhances collaboration, allowing stakeholders to review and resolve issues directly in context. Furthermore, it supports precise issue tracking, where BCF data can be linked to specific real-world elements. Proper localization also facilitates better planning and decision-making by allowing users to evaluate spatial relationships between the model and the physical environment, ultimately reducing errors and improving project efficiency

The following sections outline the methods and approaches analysed and used to align and localise the BIM models in the physical environment.

2.3.4.1 *Microsoft HoloLens 2 Mesh Scan based Localization*

The original design of the XR app with T4.4 included leveraging the HoloLens 2's spatial mesh scanning capabilities to localize and align virtual BIM models with real-world environments. This method relied on the device's depth sensors and spatial mapping features to generate a mesh of the physical surroundings, which would then be used to anchor and align the digital IFC models in the correct position relative to the physical space.

However, during testing, the HoloLens 2-generated mesh was found to be of insufficient quality for precise alignment, especially in large-scale or geometrically complex environments such as construction sites. The mesh often lacked the fidelity required for detailed localization, leading to alignment errors and reduced accuracy when overlaying virtual models (refer to Figure 17). While the overall structure, depth, and spatial relationships are well-captured, the scan exhibits limitations in resolution, manifesting as rough surfaces and a lack of fine detail. The presence of noise and artifacts, coupled with poorly defined edges, further detracts from the clarity of the scan. This inconsistency negatively impacted the immersive experience and the ability to interact with BIM data in a meaningful and accurate manner, and hence this approach was discontinued.



a)

b)

Figure 17 The Microsoft HoloLens 2 mesh scan views showcase a three-dimensional reconstruction of Holo-Light's office space.

2.3.4.2 ***Wearable-camera based Localization***

Tasks T4.1 and T4.3, along with their associated deliverables of D4.1 – "Body sensor network with integrated camera approach" and D4.3 – "Wearable-user localization algorithm", have detailed the process of localizing a wearable camera within the digital twin of a construction site from a data stream consisting of video images and IMU data of a body worn sensor system (described in D4.1). One of the localization methods employed combines the visual-inertial tracking of the visual BSN developed in T4.1 (refer to D4.1) with the detection of markers. While another method researched and investigated within T4.3 (refer to D4.3) by DFKI was the marker-less scene graph alignment method, that is currently (at the time of this deliverable) in research stage.

2.3.4.3 *Spatial Mapping of HoloLens 2 and Marker-based Localization*

T4.4 focuses on employing a slight variation of the alignment and localization methods previously discussed. It combines the spatial mapping features of the Microsoft HoloLens 2 XR device (leveraged by BIMSpace client application) and the detection of a QR-code marker.

2.3.4.3.1 Spatial Mapping of HoloLens 2

The Microsoft HoloLens 2 uses advanced Simultaneous Localization and Mapping (SLAM) and Visual-Inertial Odometry (VIO) to achieve accurate localization in its environment. SLAM allows the device to create a real-time 3D map while tracking its position, using data from depth sensors and cameras to understand spatial features. VIO enhances this by combining visual data with input from accelerometers and gyroscopes, ensuring reliable tracking even in challenging conditions like low light[12, 13].

2.3.4.3.2 HumanTech Marker Layout

As described in D3.1 – "Automated scanning pipeline", the collection of high-precision measurement data is essential for ensuring the accuracy and proper positioning of objects on construction sites. Surveyors typically place numerous crosshair markers to facilitate this process. The marker standard extends the use of these measurement markers to other functions, enabling broader access and utilization for data recording. Additionally, the measurement data is centrally stored on a project server and can be accessed via a link, often through a QR code, ensuring efficient data management and accessibility across the project.

As result of work in the EU project BIMprove, a CEN working group standard was established for Construction Site Markers (cwa18046_2023.pdf (cencenelec.eu)). These markers (refer to Figure 18) are physically represented on the construction site using

[12]https://learn.microsoft.com/en-us/hololens/hololens-environment-considerations
[13] https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-mapping

specially designed printed materials embedded with QR codes, AprilTags, or ChiliTags. Scanning these markers retrieves the corresponding BIM data and/or geolocation information from the HumanTech backend, along with additional metadata such as the marker's validity status.

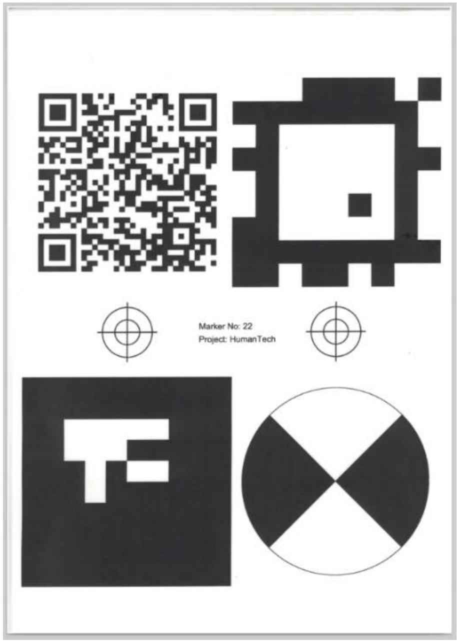


Figure 18 HumanTech marker layout.

2.3.4.3.3 Alignment and Localization in XR

Within the HumanTech project, the final marker layout consists of Apriltags and a QR code. Partner ZHAW measures each marker and creates a marker world which can be retrieved at a certain endpoint in JSON format from BIMxD. The physical markers, compliant with CEN standards, are strategically placed at key locations within the real-world environment. Refer to D4.3 – "Wearable-user localization algorithm" for detailed explanation of the marker detection.

BIMSpace XR solution uses QR codes to align the virtual BIM model with the physical environment. From BIMxD, the BIMSpace server application retrieves the marker positions that correspond to the specific spatial location within the virtual BIM model. The HoloLens 2 XR device is equipped with cameras that can scan for QR codes and once detected, the BIMSpace client application retrieves the encoded spatial data, and sends it to the server application which calculates the 3D position and 3D pose. The QR code holds the URL to an endpoint where the location of the surveyor points can be retrieved. Based on these coordinates, the virtual model is automatically aligned within the XR environment based on the encoded data i.e., BIMSpace server application utilises the spatial mapping features derived from the SLAM and VIO of the HoloLens 2 and the QR code detection to align the HoloLens 2 reference system with the BIM coordinate system for accurate visualization of the BIM model.

For testing purposes, a QR code embedded with a URL to the 3D position and 3D pose was placed in the Holo-Light office space. Upon loading the IFC file in BIMSpace client application, the user can use the in-built QR code scanning feature of the application to scan the QR code from the real environment as shown in Figure 19 and Figure 20. Automatically, based on the calculations described previously, the BIM model is aligned to the real environment providing stable positional awareness, enabling seamless interaction with both virtual and real-world objects for immersive mixed reality experiences.

Figure 19 BIMSpace Client App used to scan a QR code in the real environment.

Figure 20 A user wearing the HoloLens 2 device to scan a QR code.

3 Conclusion

The document presents an innovative approach to improving safety, efficiency, and collaboration in the construction industry through the integration of wearable technologies and advanced BIM (Building Information Modelling) visualization systems. Central to this approach is the development of the BIMSpace XR solution, a customized version of Holo-Light's Hololight Space AR/VR application, designed for use on the Microsoft HoloLens 2. By utilizing the Hololight Stream SDK, the BIMSpace solution enables real-time streaming of high-quality AR/VR applications from powerful servers to mobile devices like the HoloLens 2, significantly reducing the computational burden on mobile hardware.

BIMSpace introduces several cutting-edge features, such as the native loading of IFC files, on-demand visualization of BIM models in true scale, and seamless issue investigation through BCF file support. These capabilities allow construction workers to interact with highly detailed BIM models on-site, improving decision-making and reducing errors. Additionally, the solution's integration with partner technologies like Catenda Hub and the BIMxD platform expands its functionality and usability across various construction workflows. Within HumanTech, this integrated solution is set to be validated through Pilot 1 use case 3, 'Detection of falling hazards' demonstrating its practical benefits in real-world construction scenarios. With the use case, BIMSpace XR solution will visualise the BIM model of the pilot site and enable BCF issue investigation related to falling hazards on the construction site. The results of this validation will be documented as part of D7.1 – 'Pilot I - Dynamic semantic digital twin'.

The project also emphasizes several key target outcomes that extend beyond the immediate technological benefits. For Holo-Light, one of the primary objectives within HumanTech is to expand the use of XR (extended reality) technologies in the Architecture, Engineering, and Construction (AEC) industry, showcasing new use cases that attract potential customers which will be a potential exploitation of the project outcomes. By deploying and validating the BIMSpace solution in pilot use cases, Holo-Light within HumanTech project aims to demonstrate the practicality and efficiency of XR technologies in the AEC sector, ultimately driving market expansion across the EU and globally.

Moreover, the document highlights the competitive advantage offered by combining device-agnostic XR streaming with BIM technology. This combination positions the solution for broad applicability, enabling Holo-Light and HumanTech partners to license the technology to third parties and potential customers, further expanding their market reach. The partnerships and networks established during the project are also expected to play a key role in disseminating the technology, enhancing brand visibility, and attracting new customers.

Finally, the project emphasizes the importance of data security and privacy, ensuring GDPR compliance by processing data in real time without storing it on wearable devices. This not only enhances worker privacy but also minimizes risks associated with data breaches. Through strategic collaborations, technical advancements, and careful attention to security and compliance, the project aims to set a new standard for integrating XR technologies into construction workflows while creating new market opportunities for the involved stakeholders.

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