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# Multi-User Virtual Reality Tool for Remote Communication in Construction Projects: Bridge Maintenance Application

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**Abstract**

Effective communication between construction sites and engineering or architectural offices is critical to the success of construction projects, particularly in the maintenance of critical infrastructure such as bridges. In scenarios where distance limits the physical presence of specialists, Requests for Information (RFIs) are the primary formal exchange tool. However, issues such as incomplete data, poor quality, or delayed responses often lead to significant project delays. This study proposes a multi-user Virtual Reality (VR) platform to optimize communication workflows in these contexts. Using the Design Science Research Methodology (DSRM), an immersive environment was developed to connect up to 20 users simultaneously, integrating BIM models with support for technical details, language, and contextual factors. The tool was validated through a case study focused on the maintenance of a railway bridge, where five real RFIs were simulated. Results show that the immersive experience enhances spatial understanding, improves remote collaboration, and accelerates decision-making. Users highlighted the sense of presence and perceived usefulness, positioning this tool as an effective alternative to overcome communication barriers in geographically distributed infrastructure maintenance.

**Keywords:** virtual reality; BIM; remote communication; multi-user tool; construction projects; bridge maintenance

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**Correction Statement:** This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.



## 1. Introduction

Effective communication between construction sites and engineering or architectural offices is critical to the success of construction projects [1,2], particularly in the maintenance of critical infrastructure such as bridges. Accurate and timely transmission of information enables the prevention of errors, cost overruns, and delays [3–5]. However, various obstacles—including inefficient systems, language barriers, cultural differences, and logistical limitations [6–9]—continue to hinder interactions, especially when specialists are geographically distant.

Traditional methodologies such as Lean Construction (LC) and Building Information Modeling (BIM) have improved collaboration and communication within the Architecture, Engineering, Construction, and Operation (AECO) sector [10–14]. Nevertheless, challenges related to trust, organizational fragmentation, and team dispersion persist [6–9]. In this context, Distance Theory offers a useful framework to analyze and mitigate communication barriers through eight dimensions—such as organizational, geographical, cognitive, and semantic distances—supported by the Gap Model [15].

In bridge infrastructure management, effective communication becomes even more critical due to the increasing integration of remote sensing technologies, point cloud modeling, and digital twins for inspection, maintenance, and monitoring [16]. Although these technologies provide highly detailed representations and real-time data, their full potential relies on ensuring that multidisciplinary teams can accurately interpret, discuss, and act upon the information [6,17]. When physical inspections are constrained by safety, costs, or logistics, Requests for Information (RFIs) serve as the primary formal channel for clarifying technical issues [18]. However, traditional RFI workflows often suffer from incomplete information, unnecessary iterations, and delayed responses, undermining the benefits of digital data acquisition [1].

Alternatives like Extreme Collaboration Meeting Rooms, which integrate BIM and advanced visualization technologies, have aimed to improve communication, but their high cost and dependence on fixed infrastructure limit their scalability in geographically dispersed projects [19]. In response, Virtual Reality (VR) emerges as a promising alternative, offering immersive environments accessible from multiple locations [20]. VR enables shared spatial understanding, real-time interaction, and informed decision-making, addressing many of the physical and organizational constraints inherent in bridge maintenance projects [21–26].

Despite its expanding use in training, planning, and asset management [21,24–27], the specific application of VR to optimize remote communication workflows in infrastructure maintenance remains underexplored. Addressing this gap, this study develops and validates a multi-user VR platform designed to enhance collaboration and decision-making in bridge maintenance contexts. The tool connects up to 20 users in a shared immersive environment, integrating BIM models enriched with technical information, measurement capabilities, and multilingual support. Validation was conducted through a real-world case study on the maintenance of a century-old railway bridge, simulating five actual RFIs to assess the platform's impact on communication efficiency, collaboration, and decision-making.

## 2. Background

### 2.1. Communication Challenges in Bridge Maintenance Projects

Effective communication between teams is essential to the success of projects in the Architecture, Engineering, Construction, and Operation (AECO) industry [2]. This is especially critical in the maintenance of bridge infrastructure, where multidisciplinary collaboration, timely technical decisions, and the integration of remote data sources play a fundamental role [3]. Miscommunication can lead to misinterpretation of technical conditions, delayed interventions, increased costs, and even risk to structural safety [7,28]. Despite the growing use of inspection technologies—such as remote sensing, point cloud modeling, and digital twins [16]—the effectiveness of maintenance projects still largely depends on how well information is transmitted, interpreted, and acted upon by geographically distributed teams [6,17]. Formal channels such as Requests for Information (RFIs) aim to standardize technical queries during maintenance activities [1]; however, they frequently suffer from delays, incomplete documentation, and repeated iterations [15]. Studies have highlighted that communication inefficiencies can reduce project success rates by up to 28% and significantly impact project schedules and budgets [2,3,7].

Previous research has primarily focused on improving the accuracy and automation of data collection through sensing technologies [16,29], but comparatively little attention has been given to how this information is collaboratively interpreted and operationalized among teams operating remotely. This gap underlines the need for innovative communication workflows that complement the technological advances in asset monitoring with more effective remote decision-making processes.

*2.2. Distance Theory and Strategies for Communication Improvement*

Communication challenges in construction and infrastructure maintenance projects can be better understood through the lens of Distance Theory [30]. This theory identifies eight types of distances that affect the effectiveness of communication between individuals, artifacts, and activities: geographical, organizational, psychological, cognitive, semantic, adherence, navigational, and temporal distances [15]. For instance, geographical distance arises when participants are physically separated, while cognitive distance emerges when team members have different levels of technical understanding or expertise [31]. Navigational distance refers to difficulties in locating related information across distributed documents or models [15]. These distances contribute to delays, misinterpretations, and fragmentation in decision-making processes [30].

The Gap Model, derived from Distance Theory, proposes specific practices to reduce or mitigate these communication barriers [15]. Traditional strategies, such as co-location in Extreme Collaboration Meeting Rooms, have attempted to address these gaps by bringing participants together and integrating tools like BIM visualizations and large-format displays [32]. However, their effectiveness is limited by high implementation costs, low portability, and the impracticality of co-location [19], for example, for infrastructure assets such as bridges, which are often located in remote or difficult-to-access areas.

While some studies have recognized the relevance of Distance Theory to improve communication in distributed engineering projects [15], there is a notable lack of research applying these principles systematically to bridge maintenance workflows, particularly considering the integration of digital twins, point clouds, and remote inspections. This reveals a significant opportunity to explore new communication methodologies adapted to the realities of infrastructure maintenance.

*2.3. Virtual Reality and Digital Tools for Enhancing Remote Collaboration*

The application of digital tools—such as Building Information Modeling (BIM), point cloud technologies, and digital twins—has greatly enhanced the visualization, documentation, and monitoring of bridge conditions [33]. Remote sensing technologies now allow for detailed asset characterization without the need for constant physical inspections, generating valuable data for decision-making. Nevertheless, the availability of detailed digital data does not automatically guarantee efficient communication or collaborative decision-making. Traditional workflows for discussing asset conditions and planning interventions often rely on static reports, emails, and fragmented meetings [1,6,15], which fail to exploit the immersive and interactive potential of digital models.

Virtual Reality (VR) has emerged as a promising technology to bridge this gap. VR enables multi-user, immersive environments where technical teams can collaboratively navigate 3D models, interact with technical attributes, and discuss interventions in real time, regardless of their physical locations [21,27]. Applications of VR in construction have shown improvements in training, planning, and safety management [21–26]; however, its specific use for managing RFIs and enhancing communication in bridge maintenance remains underexplored. Most existing research has focused either on VR for education, training simulations, or design review [34–36], but very few studies address how VR can be systematically integrated into maintenance communication workflows, particularly in the context of geographically distributed bridge infrastructure. Furthermore, there is a lack of validated methodologies that align immersive collaboration with practical processes like RFI management.

Thus, while technological capabilities for remote sensing and modeling have advanced significantly, the gap persists in translating these digital assets into effective collaborative workflows. This research aims to address this unmet need by proposing a VR-based multi-user platform specifically designed to optimize remote communication for bridge maintenance projects, enabling more agile, accurate, and informed decision-making.

## 3. Research Methodology

This study focuses on improving communication management in construction projects through the use of virtual reality. To achieve this, the Design Science Research Methodology (DSRM) will be employed, as it provides a practical framework for conducting research projects that involve the development of artifacts. The following stages are considered: (1) Problem identification and motivation; (2) Definition of the objectives of a potential solution; (3) Design and development; (4) Demonstration; and (5) Evaluation [37]. Figure 1 illustrates the activities, tools, and methods used in the development of this research.

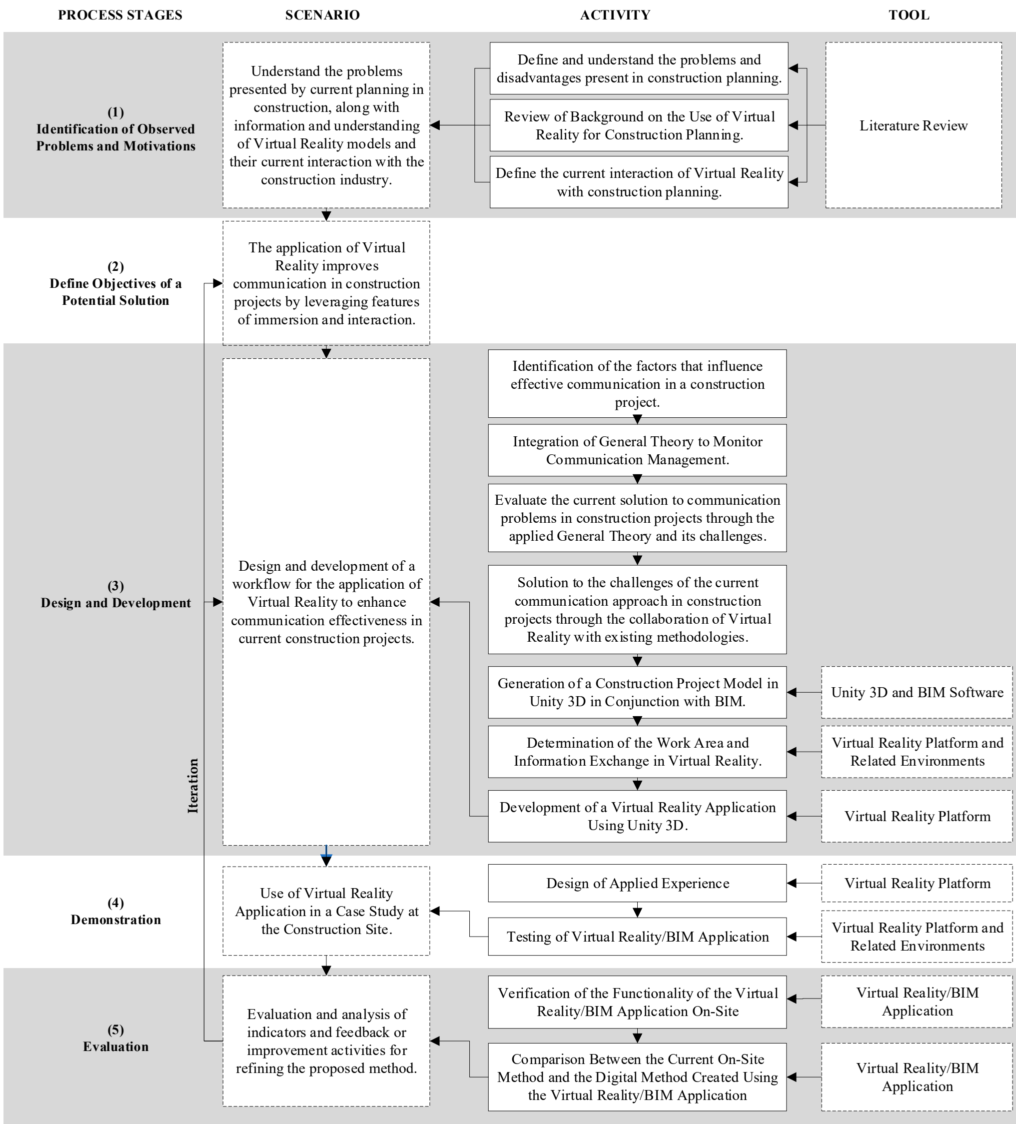



**Figure 1.** Research methodology.

In the first stage, a literature review was conducted, based on Web of Science and Scopus. Its objective was to identify the challenges in construction project planning, with a focus on communication, and to analyze emerging technologies used in the sector, highlighting the potential of Virtual Reality to overcome these issues. In the second stage, the objective of a potential solution was established. VR was proposed as a solution to improve communication in projects, leveraging its immersive and interactive capabilities to enhance collaboration among the stakeholders involved.

The third stage proposed a method based on Distance Theory to identify and mitigate communication barriers ($B_i$) using the Gap Model and current practices such as BIM and Lean Construction (LC). The concept of an "Extreme Collaboration Meeting Room" is proposed which, despite its limitations, integrates Virtual Reality (VR) with the BIM Table. A model was developed using Unity 3D and BIM to manage communication in virtual environments.

In the fourth stage, the method will be applied to a case study using Unity 3D and the proposed approach to resolve RFIs in real time. In the fifth stage, its effectiveness and usability in managing communication in construction projects will be validated, contributing to an innovative approach for the sector. As part of the evaluation process in this fifth stage, the survey will be conducted in two distinct moments: a first measurement before the virtual reality experience and a second immediately after its completion. The sample will consist of six subject-matter experts, and the questionnaire will incorporate specific items designed to verify the consistency of the responses obtained.

## 4. Proposed Workflow

The existence of communication barriers in construction projects has motivated the development of methods to mitigate them. Distance Theory and the Gap Model provide an initial framework, but their application in construction requires the integration of methodologies such as Lean Construction (LC), Building Information Modeling (BIM), and immersive technologies like Virtual Reality (VR). The combination of these tools, along with the BIM Table, enables the overcoming of geographical and communicative barriers, facilitating collaboration and decision-making through virtual environments [21].

A method is proposed based on Distance Theory and specific practices, in which participants located in different geographic areas use VR headsets (HTC Vive and HTC Vive Pro 2, HTC Corporation, New Taipei City, Taiwan; Meta Quest 3, Meta Platforms Inc., Menlo Park, CA, USA) to interact in real time with 3D BIM models. The experiments were carried out in Barcelona, Spain, at the facilities of CIMNE, Universitat Politècnica de Catalunya (UPC), and in Valparaíso, Chile, at the TIMS Laboratory of the School of Civil Engineering, Pontificia Universidad Católica de Valparaíso (PUCV). This approach enables visualization, editing, and collaboration on technical details, breaking down communication barriers and optimizing the construction process. To enhance communication in construction projects through the use of Virtual Reality (VR), a structured method is proposed, consisting of four stages, as illustrated in Figure 2:

1. **Identification of project documentation:** 2D plans and elevations are analyzed to define the technical characteristics and key elements of the project, such as modifiable or conflicting components. Additional relevant information is also collected, and tools such as Lean Construction (LC) and BIM are identified for use in project management.
2. **BIM of the project:** A three-dimensional (3D) model is created based on the 2D data, incorporating details such as materials, dimensions, and specific characteristics of structural elements. This model allows for a more realistic visualization of the project, optimizing traditional communication workflows, such as the handling of Requests for Information (RFIs). The proposed modified workflow aims to overcome communication barriers in this process by detailing changes in the interactions between the construction site and the office.

3. **Implementation of VR software:** The project's BIM model was exported from Autodesk Revit 2022 (Autodesk Inc., San Rafael, CA, USA) and transferred to the Unity 3D Virtual Reality environment using Unity 2022.3.10f1 (Unity Technologies, San Francisco, CA, USA). During this process, technical specifications and interactive functions are integrated, such as element manipulation, measurements, and multilingual options. Real-time collaboration is enabled through immersive devices (VR headsets), facilitating virtual meetings among participants located in different locations and allowing for individual VR walkthroughs of the project.
4. **Creation of the communication management method:** An executable VR-based application is developed to enhance the workflow in immersive collaborative meetings. This method includes eight practices designed to mitigate communication barriers, reducing response times for RFIs. Meetings are coordinated virtually, protocols are applied to resolve technical questions, and the results are documented and shared via a cloud platform accessible to all participants. This workflow proposes an innovative approach to optimize communication between the construction site and the office, increasing efficiency in construction project management and overcoming traditional barriers through the use of VR and BIM tools.

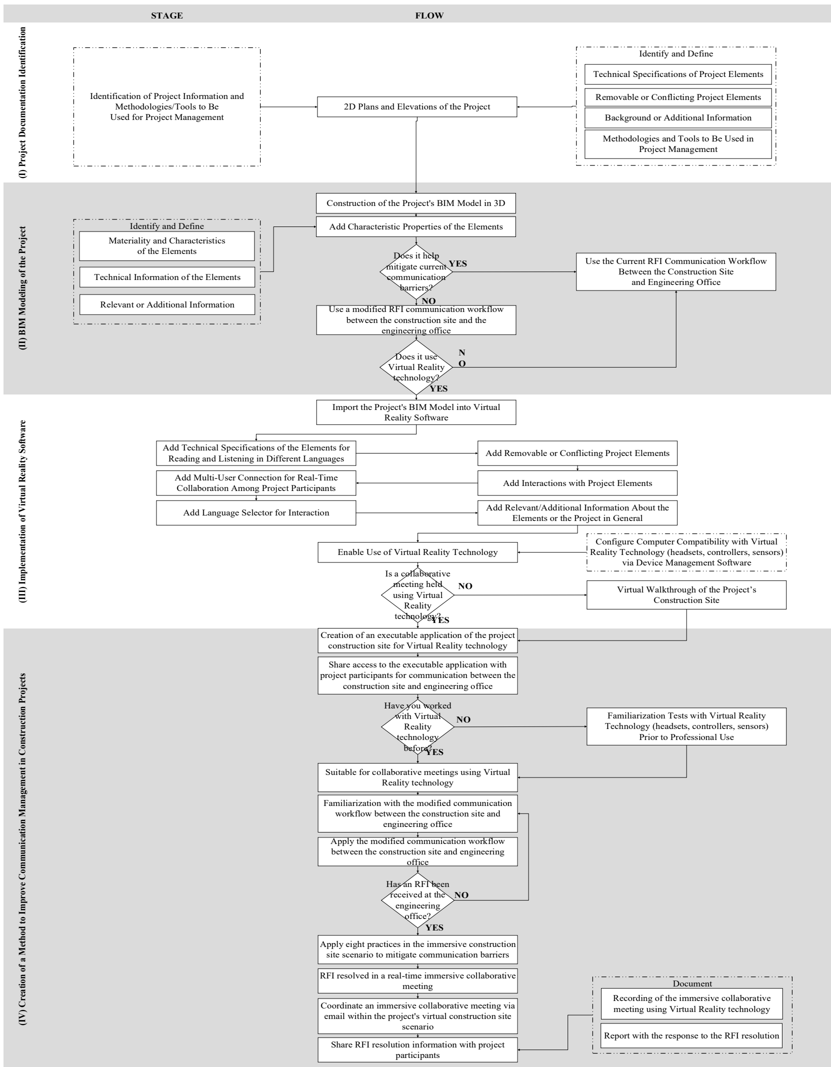



**Figure 2.** Flowchart for the creation of a method for the use of Virtual Reality to improve communication in construction projects.Note: The current and proposed communication workflows between the engineering office and the construction site are explained in Figure 3.

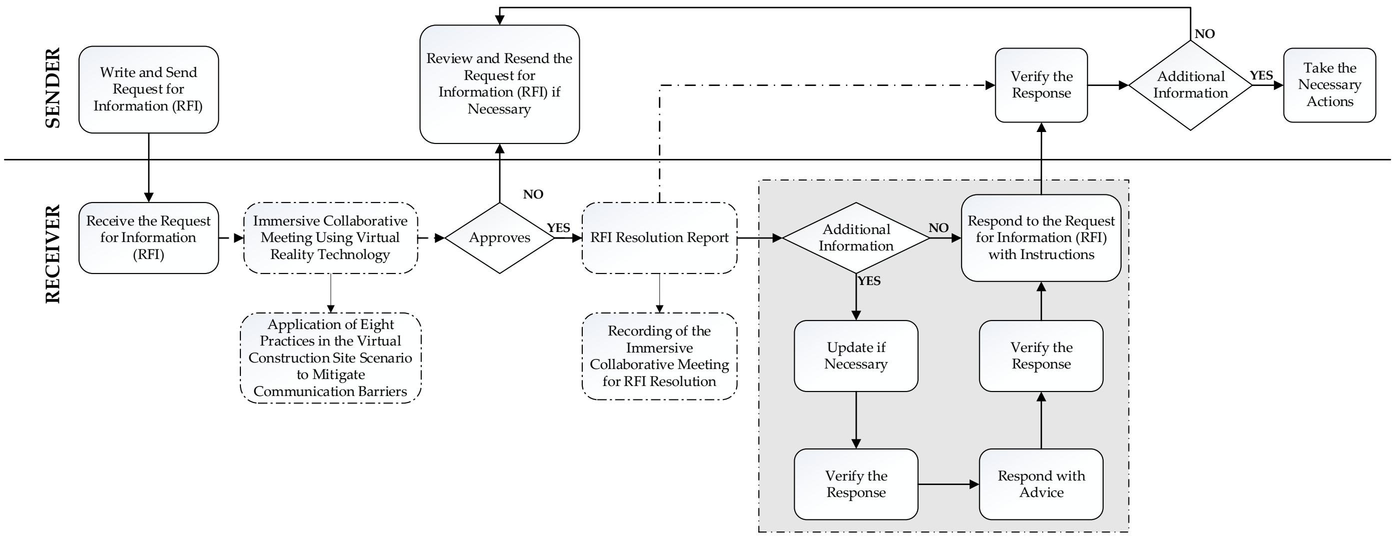



**Figure 3.** Flowchart of the Request for Information (RFI) Issuance and Response Process. Adapted from [1].

Before the issuance of the Request for Information (RFI), as explained in Figure 3, the sender is currently required to classify it in advance according to the relevant category, which is done based on Table 1 of the RFI analysis, shown in gray.

**Table 1.** Modified Flowchart of the Request for Information (RFI) Analysis. Adapted from [1].

| ID * | RFI Typology Analysis * | Classification * | Sub-Classification * | CB Typology Analysis | Communication Workflow |
|---|---|---|---|---|---|
| 1 | If the description proposes a solution | Classify as Approval | NA[1*] | If it originates from political/community interference<br>If it originates from poor listeners<br>If it originates from lack of trust<br>If it originates from unclear objectives<br>If it originates from conflicting cultural values<br>If it originates from unclear communication channels<br>If it originates from an ineffective notification system<br>If it originates from limited resources<br>If it originates from information filtering<br>If it originates from language difficulties<br>If it originates from lack of necessary skills | Issue RFI with Modified Workflow |
| 2 | If a design solution is requested based on the available information | Classify as Design Solution | NA[1*] | | |
| 3 | If clarification or additional information is requested | Classify as Information Clarification | Conflict | | |
| | | | Incorrect | If it originates from poor leadership<br>If it originates from conflicting business/industrial ethics | Issue RFI with Current Workflow |
| | | | Questionable | If it originates from religious issues<br>If it originates from age differences | |
| | | | Insufficient | | |
| 4 | Other | Classify as Other | | | |

* Current Flowchart of the Request for Information (RFI) Analysis. NA[1*] = Not Applicable.

For this research, the following Modified Communication Workflow is proposed for handling Requests for Information (RFIs) between the construction site and the engineering office, based on the current process. Figure 3 illustrates the contrast: the proposed method uses a modified flowchart to manage RFIs in construction projects through Virtual Reality (VR). This approach includes an initial classification of the RFI, along with an additional classification based on the Communication Barrier identified by the sender, who has greater knowledge of the issue and proposes the communication flow to be followed according to the barrier category assigned to the RFI (Table 1).

The process eliminates unnecessary iterations through collaborative meetings in a virtual environment, where participants access a shared cloud containing project information. After the meeting, if the request is approved, a report is generated and uploaded to the cloud along with a recording of the session, ensuring that all stakeholders have access to detailed information.

## 5. Development

### *5.1. Distance Theory as the Basis for a Method to Improve Communication in Construction Projects*

The literature has identified 15 communication barriers that affect communicative effectiveness in construction projects, reflecting challenges related to time, cost, and project scope. To determine the critical aspects that need to be addressed within these barriers, Distance Theory has been employed. This theory distinguishes eight types of distances between people, artifacts, and activities, providing key elements for evaluating communication barriers and also proposing eight practices to eliminate them (GAP model). Table 2 presents the Gap Model, where for each type of distance described in Distance Theory (as shown in Table 3), there is a corresponding practice that reduces or mitigates it (left gray area).

**Table 2.** Classification of Communication Barriers Based on Distance Theory. Adapted from [6,15].

| Distance Theory | | GAP Model Practices | | | | | | | | Communication Barriers | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Role Collaboration | Separated Evaluators | Documentation | Alignment of Document | Structures and Tracking | Cross-Artifact Reviews | Incremental Software Engineering | Automated Testing | Use of Alignment Metrics | Political/Community Interference | Poor Listeners | Poor Leadership | Unclear Objectives | Conflicting Cultural Values | Unclear Communication Channels | Ineffective Notification System | Limited Resources | Information Filtering | Conflicting Business/Industrial Ethics | Lack of Necessary Skills | Lack of Trust | Language Difficulties | Age Differences |
| **ID** | **Distance** | **AP1** | **AP2** | **AP3** | **AP4** | **AP5** | **AP6** | **AP7** | **AP8** | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** | **B7** | **B8** | **B9** | **B10** | **B11** | **B12** | **B13** | **B14** | **B15** |
| **D1** | Geographical | ✓ | | | | | | | | ✓ | | | | | ✓ | ✓ | ✓ | | | | | | ✓ | |
| **D2** | Organizationa | | | | | | | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | | | ✓ | | |
| **D3** | Psychological | ✓ | | | ✓ | | | | | ✓ | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **D4** | Cognitive | ✓ | ✓ | ✓ | ✓ | | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **D5** | Adherence | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | | ✓ | | | | | | | |
| **D6** | Semantic | ✓ | | | ✓ | ✓ | ✓ | | | | | | | ✓ | | ✓ | | | ✓ | | | ✓ | ✓ | |
| **D7** | Navigational | | | | ✓ | | | | | ✓ | ✓ | | | | ✓ | ✓ | ✓ | | | | | | | |
| **D8** | Temporal | ✓ | | | | | ✓ | ✓ | | ✓ | ✓ | | | | ✓ | ✓ | ✓ | | | | | | | |
| **ID** | **Distance** | **AP1** | **AP2** | **AP3** | **AP4** | **AP5** | **AP6** | **AP7** | **AP8** | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** | **B7** | **B8** | **B9** | **B10** | **B11** | **B12** | **B13** | **B14** | **B15** |

Nota: The gray shading in the left column is used to enhance visualization and distinguish the communication barriers from the practices proposed in the Gap Model. Note: The check marks (✓) indicate a conceptual relationship. On the left side (with gray background), they show which Gap Model practices reduce each type of distance. On the right side (without background), they represent the distances associated with each communication barrier.

Based on this model (right area of the table), the 15 communication barriers identified in the literature for construction projects are evaluated, determining which type of distance they fall under and, consequently, which practices are appropriate for their mitigation or reduction. For example, the communication barrier "B4—Unclear objectives" is categorized under “D2—Organizational” and “D4—Cognitive” distances, and can be mitigated or reduced through practices AP1, AP2, AP3, AP4, and AP6.

**Table 3.** Distance Theory. Source: Adapted from [15].

| Sigla | Distance | Definition |
|---|---|---|
| D1 | Geographical Distance | The physical distance between the workplace locations of the actors. |
| D2 | Organizational Distance | The distance between the positions of the actors within an organizational structure. |
| D3 | Psychological Distance | The subjective level of effort perceived by one actor as required to communicate with another actor. |
| D4 | Cognitive Distance | The difference in cognitive levels between actors, i.e., knowledge, competence, and understanding. |
| D5 | Adherence Distance | The level of similarity between the content of an artifact and the actual situation. |
| D6 | Semantic Distance | The level of similarity in meaning between two related artifacts. |
| D7 | Navigational Distance | The difference in the location of related parts across different artifacts required to navigate from one to another. |
| D8 | Temporal Distance | The time difference when related activities are performed. |

### *5.2. Implementation: Hardware and Software Used*

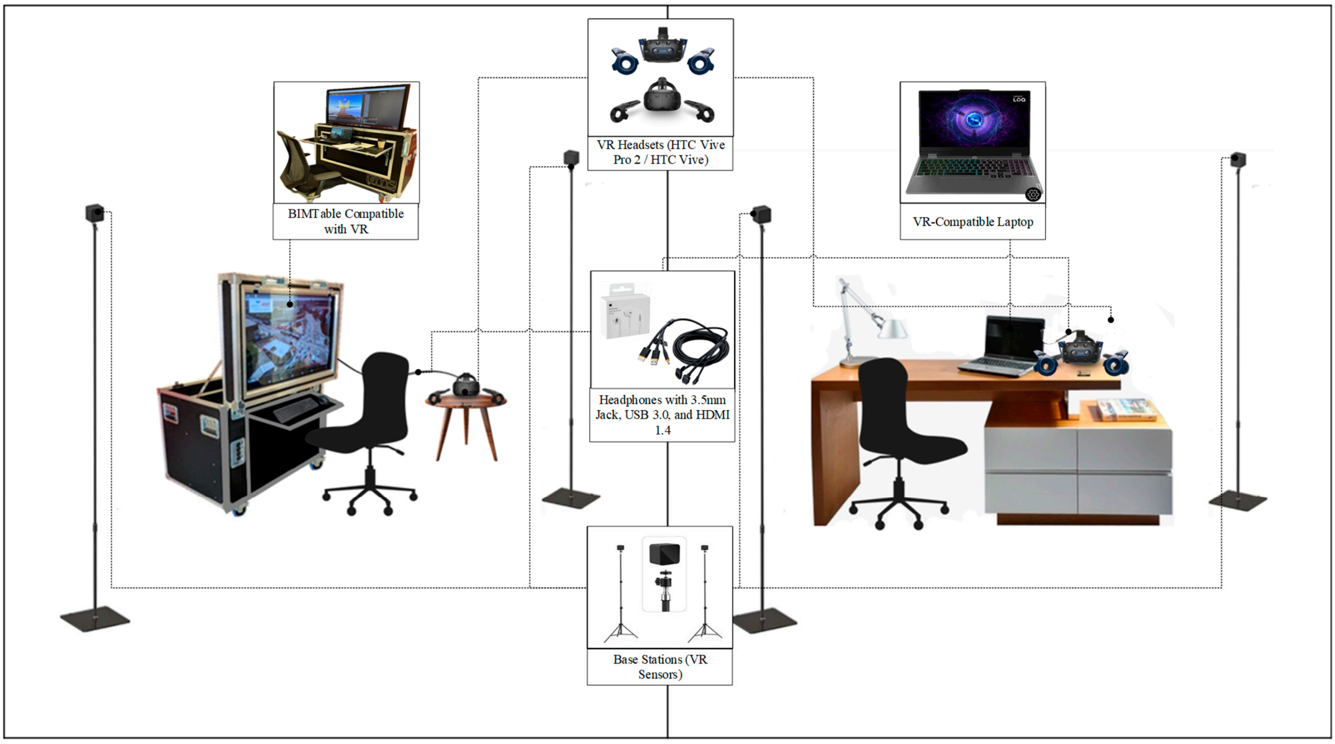
The development of the VR experience requires two computers with specific technical specifications. This table includes the minimum required features for the BIMTable computer (developed by the International Centre for Numerical Methods in Engineering, CIMNE, Barcelona, Spain, simulating the construction site), the laptop (simulating the engineering office), as well as the recommended specifications (Table 4).

**Table 4.** Computer Specifications Compatible with VR Technology.

| Component | Minimum Requirements | BIMTable | Laptop | Recommended |
|---|---|---|---|---|
| Processor | Intel Core i5-4590/AMD FX 8350 or higher | Intel Core i7-9700 | Inter Core i7-8750 | Intel Core i5-4590/AMD Ryzen 5 1500X or higher |
| Graphics Card | NVIDIA GeForce GTX 970/AMD Radeon R9 290 or higher | AMD Radeon RX 5700 XT | NVIDIA® GeForce RTX™ 2070 | NVIDIA GeForce GTX 1060/AMD Radeon RX 480 or higher |
| RAM | 4 GB or more | 16 GB | 16 GB | 8 GB or more |
| Video Connection | HDMI 1.4 o DisplayPort 1.2 or higher | HDMI 1.4 | HDMI 1.4 | HDMI 1.4 o DisplayPort 1.2 or higher |
| USB Ports | 1× USB 2.0 or higher | USB 3.1 | USB 3.0 | 1× USB 3.0 o superior, 1× USB 2.0 or higher |
| Operating System | Windows 7 SP1, Windows 8.1 o Windows 10 | Windows 11 | Windows 11 | Windows 10 |
| Software | SteamVR | SteamVR | SteamVR | SteamVR |
| Available Storage | Play area of at least 1.5 m on each side | Play area of at least 1.5 m on each side | Play area of at least 1.5 m on each side | Play area of at least 2 m on each side |
| Accessories | HTC Vive model sensors and base stations | HTC Vive model sensors and base stations | HTC Vive model sensors and base stations | HTC Vive model sensors and base stations |

The VR experience uses HTC Vive and HTC Vive Pro 2 headsets (HTC Vive and HTC Vive Pro 2, HTC Corporation, New Taipei City, Taiwan)but compatibility with devices such as motion sensors, headsets, and controllers is managed by the computer through SteamVR software (version 2.2, the latest available at the time of the experiments). Therefore, the computer’s specifications—especially the graphics card—are crucial for performance.

To properly carry out the modified communication workflow through RFIs, an optimal space is required to conduct tests comfortably. Thus, the two spaces were arranged as shown in Figure 4 below.




(**a**) (**b**)

**Figure 4.** Scenarios Used in the Case Study. (**a**) Construction Site; (**b**) Engineering Office.

To develop and validate the Case Study, various functionalities and user interactions within the VR experience, as well as with participating project collaborators, are programmed. These are detailed below.

## *5.3. Development of Functionalities*

To meet the requirements of the proposed method, nine functionalities were programmed, enabling interactions in virtual reality both with digital models and among users. These include: (1) functionalities for inspecting and performing collaborative tasks, (2) viewing and listening to the technical specifications of elements, (3) navigating through the virtual construction site, (4) collaborating and communicating via voice and in real time, (5) interacting with project information in the user's preferred language, (6) viewing and/or modifying different layers associated with project roles, (7) collaborating and communicating from different geographic locations, (8) using the BIMTable at the construction site and a computer at the engineering office, and (9) leveraging compatibility with Virtual Reality technologies.

### 5.3.1. Interactive Tools for Collaboration in Virtual Reality

The application incorporates four key functionalities that enable direct interaction with digital models, whether in single-user or multi-user environments. These tools facilitate communication and collaborative analysis within the virtual environment. The available functionalities are as follows: distance measurement, screenshot capture, object grabbing and manipulation, and object marking. All of these tools are available at the "Elements and Materials Stations" and are activated using the lower trigger on either the left or right controller, providing an intuitive and efficient interaction experience (Figure 5a). Each of these tools is detailed below.

- **Distance Measurement.** This tool enables the measurement of both short and long distances. For long-distance measurement, red cross markers available at the tool station are used (Figure 5a,b). To use it, the user must place one cross at the starting point and another at the endpoint. The straight-line distance between the two is displayed in the "Material Technical Sheet" menu at the bottom of the information panel (Figure 5c). On the other hand, for short-distance measurement, rays emitted from the virtual hands are used. When these rays collide with objects within the model, the distance between the collision points is shown in the same menu, just below the long-distance measurement (Figure 5d).
- **Object Grabbing and Manipulation.** Users can grab and hold objects within the virtual environment. By pressing the trigger on the VR headset controllers (simulating the action of closing the hand to grasp an object), the object is held, and the virtual hand replicates the action by closing. When the user releases the trigger, the object remains suspended in the air, preventing it from falling and enhancing object usability (Figure 5e).
- **Object Marking.** To mark specific elements in the model, black crosses available at the "Tools and Elements Station" are used (Figure 5f). Users can pick up a cross and place it at the desired point within the virtual environment, facilitating communication and documentation of key areas in the model.

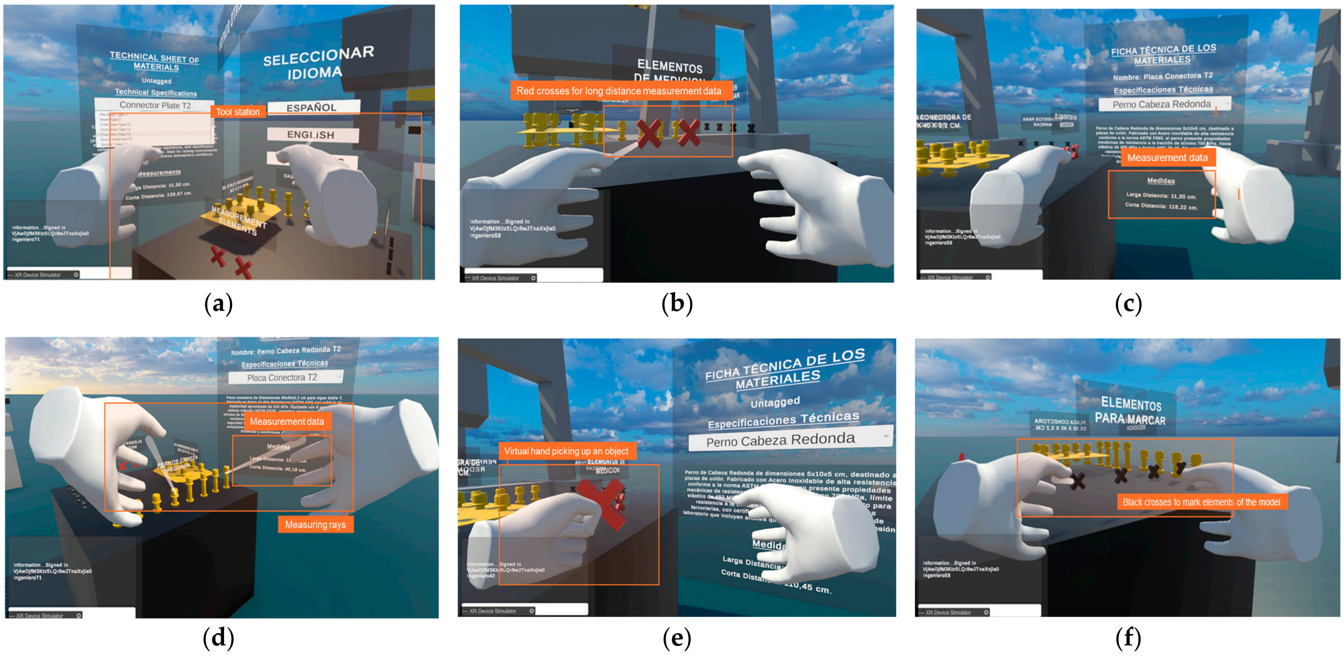



**Figure 5.** Functionalities of the Interactive Tools for Collaboration in Virtual Reality. (**a**) Tool station; (**b**) Red crosses for long distance measurement data; (**c**) Measurement data; (**d**) Measurement data and measuring rays; (**e**) Virtual hand picking up an object; (**f**) Black crosses to mark elements of the model. Note: The figures intentionally present different language settings (English, Spanish, and Portuguese) to demonstrate the multilingual options available in the VR simulation.

### 5.3.2. Visualization and Audio Playback of Technical Specifications

While navigating the virtual construction site, the user can access the "Material Technical Sheet" menu by pressing the X button on the right-hand controller. This menu displays the name of the structural element being pointed at by the rays emitted from the virtual hands (Figure 6a). Below the name, a box appears that, when clicked using the trigger on either controller, expands to show a list of the elements present in the scene (Figure 6b). From this list, the user can select the element whose technical specifications they wish to consult, such as the one currently being pointed at. By selecting it with the trigger, the user can read and listen to its technical specifications (Figure 6c). Additionally, this dropdown menu adapts to the language selected in the "Language Menu" (Figure 6d), ensuring that both the text and audio are presented in the preferred language (Spanish, English, or Portuguese).

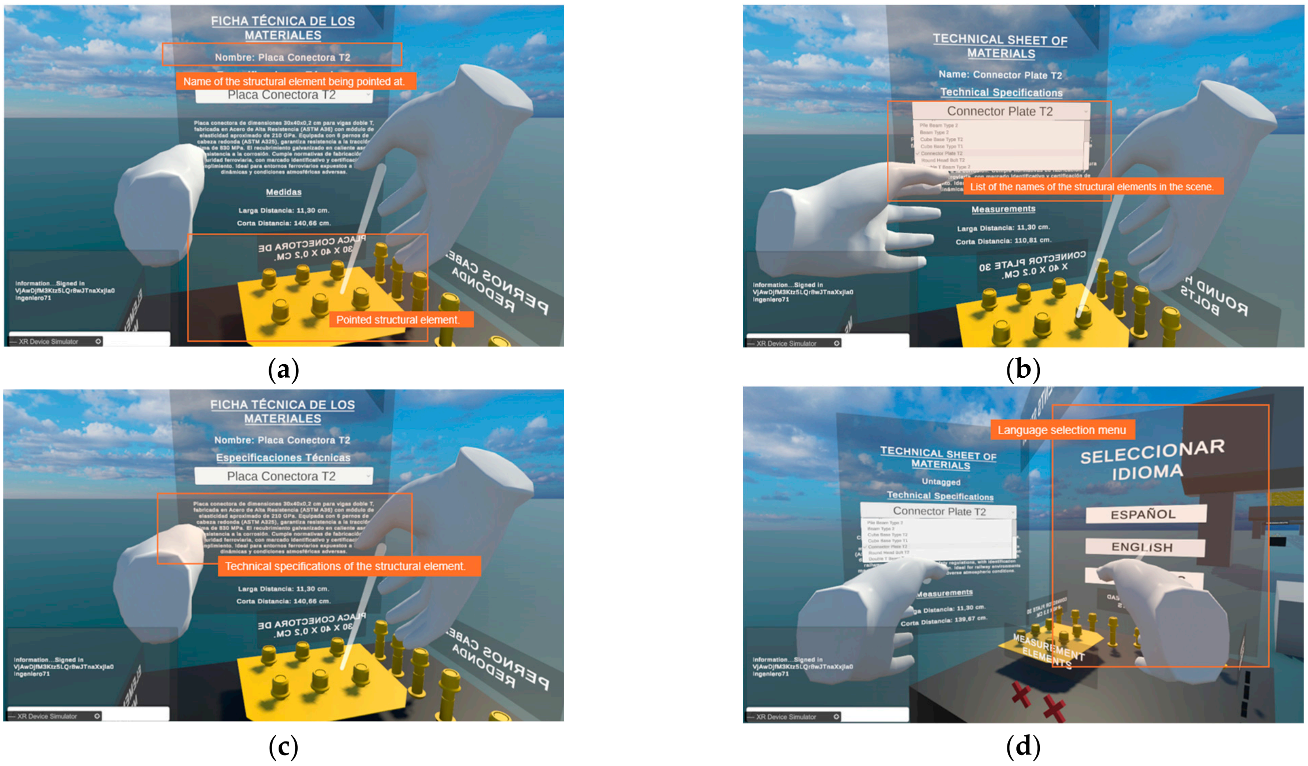



**Figure 6.** Functionalities of the Technical Specifications Visualization and Audio Playback Tool. (**a**) Name of the structural element being pointed at and pointed structural element; (**b**) List of the names of the structural elements in the scene; (**c**) Technical specifications of the structural element; (**d**) Language selection menu.

#### 5.3.3. Virtual Walkthrough of the Virtual Construction Site

Upon entering the VR application for the case study, the user is placed in a virtual construction site that can be explored using the virtual reality controllers (Figure 7a). The user is represented as an avatar equipped with white gloves, safety glasses, and a yellow hard hat; all other participants who join will appear with the same appearance (Figure 7b). In the environment, the avatar floats above the ground and can move freely, flying to any location on the railway bridge. This format ensures that all areas of the bridge are accessible, allowing users to easily and thoroughly explore the construction site.

As the user navigates the site, key project information is displayed in informational balloons (Figure 7c), including transverse axes, names of critical objects, tools and station elements, bridge axes, material technical specification menus, and a language selection option for communication within the virtual environment (Figure 7d–h). In addition, the project is inspected safely and accessibly at a 1:1 scale, facilitating the identification and evaluation of critical elements.

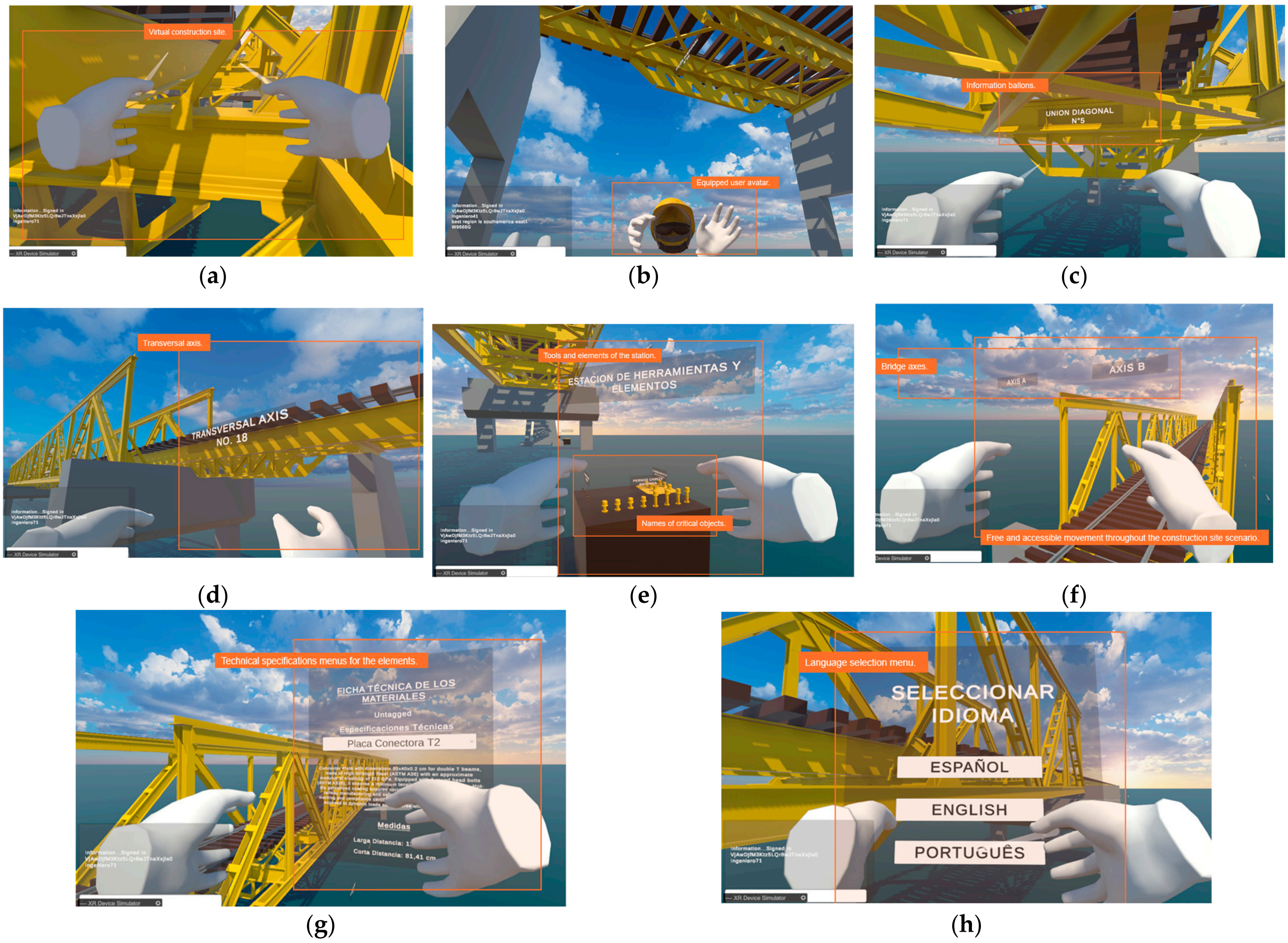
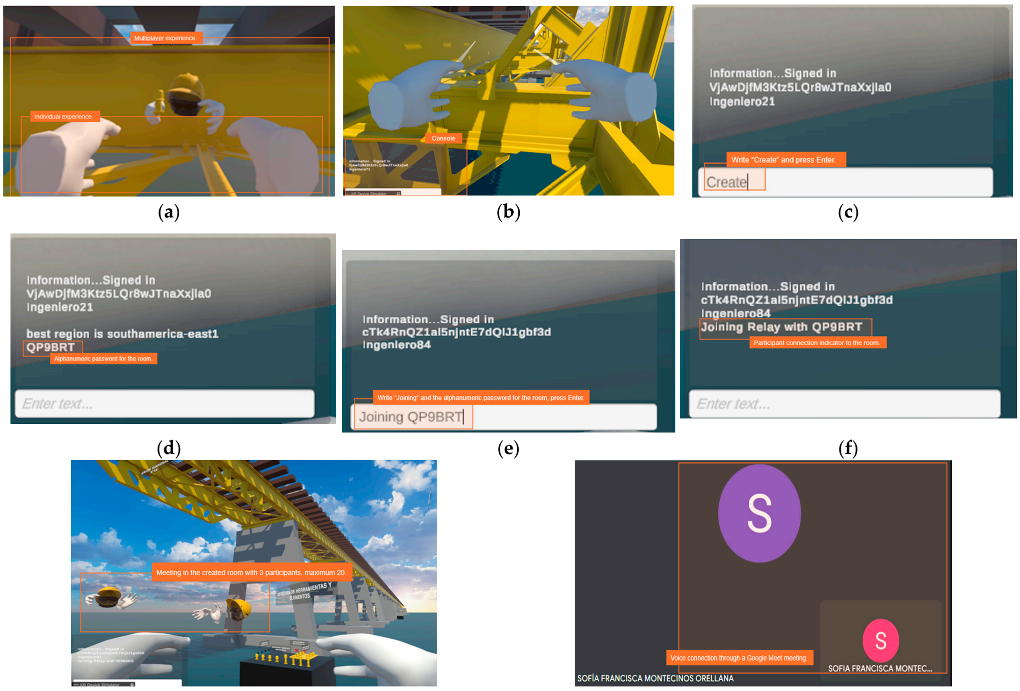



**Figure 7.** Functionalities of the Virtual Walkthrough Tool for the Virtual Construction Site. (**a**) Virtual construction site; (**b**) Equipped user avatar; (**c**) Information ballons; (**d**) Transversal axis; (**e**) Tools and elements of the station and names of critical objects; (**f**) Free and accessible movement throughout the construction site scenario and bridges axis; (**g**) Technical specifications menus for the elements; (**h**) Language selection menu.

### 5.3.4. Real-Time Voice Communication and Collaboration

The Virtual Reality (VR) experience offers two modes: a single-user experience and a multi-user experience (Figure 8a), which allows up to 20 different users to participate in the same session in real time. By default, the application is set to single-user mode. For others to join the same room, they must use the console located in the lower-left corner of the VR application, accessible from a computer (Figure 8b). To create a room, the user must type "*Create*" in the console and press Enter (Figure 8c). Once created, the console will generate a six-character alphanumeric password in uppercase (e.g., BJKG65) (Figure 8d). This code must be shared by the room creator with the other participants. To join, participants must type "*Joining BJKG65*" in the console and press Enter (Figure 8e,f). Upon connecting, users will be able to see the avatars of other participants within the session (Figure 8g).

To collaborate via voice, it is recommended to hold a remote meeting through platforms such as Zoom or Google Meet while working in the VR construction site environment. The VR headsets detect the meeting, allowing users to listen and speak as if using a built-in microphone, thereby facilitating real-time collaboration (Figure 8h).

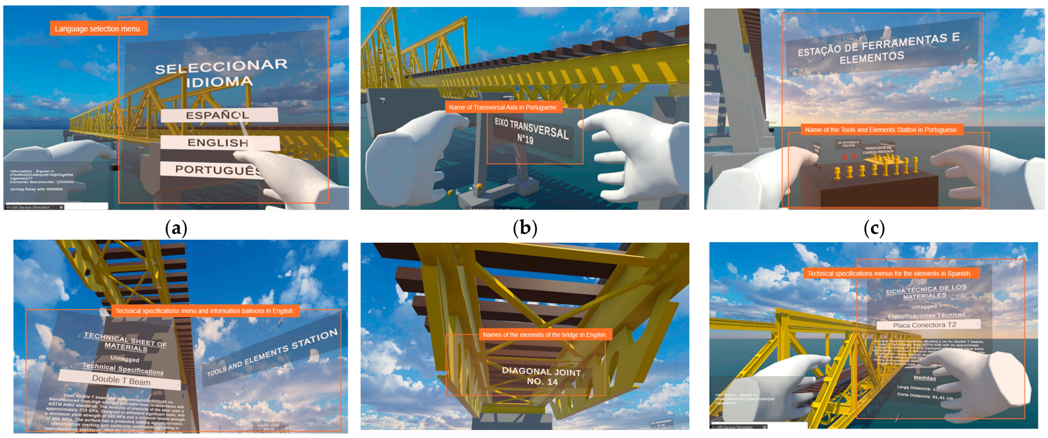



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**) (**h**)

**Figure 8.** Functionalities of the Real-Time Voice Communication and Collaboration Tool. (**a**) Individual experience and multiplayer experience; (**b**) Console; (**c**) With "Create" and press Enter; (**d**) Alphanumeric password for the room; (**e**) Write "Joining" and the alphanumeric password for the room, press Enter; (**f**) Participant connection indicator to the room; (**g**) Meeting in the created room with 3 participants, maximum 20; (**h**) Voice connection through a Google Meet meeting. Note: In Figure (h), the simulation represents a Google Meet video call between two people. The different colors of the letter "S" indicate two distinct participants, both with names starting with "S", located in different places during the call.

#### 5.3.5. Interaction with Project Information and Communication in the Preferred Language

When launching the VR application, you can open the "Select Language" menu by pressing the Y button on the right-hand controller. Using the rays emitted from the virtual hands, you select the desired language and confirm your choice by pressing the controller's trigger (Figure 9a).




(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

**Figure 9.** Functionalities of the Tool for Interaction with Project Information and Communication in the Preferred Language. (**a**) Language selection menu; (**b**) Name of Transversal Axis in Portuguese; (**c**) Name of the Tools and Elements Station in Portuguese. (**d**) Technical specifications menu and information ballons in English; (**e**) Names of the elements of the bridge in English; (**f**) Technical specifications menus for the elements in Spanish.

Once selected, all project information—such as material technical specification sheets, element names, menus, axis labels, and any available text or audio—is presented in the chosen language (Figure 9b–f). The system offers three language options: Spanish, English, and Portuguese, which can be adjusted according to the needs of the project and its participants. Upon selection, the entire virtual construction site environment automatically adapts to the preferred language, including both the reading and audio playback of technical specifications in the selected language.

#### 5.3.6. Viewing and/or Editing the Project Role Layers

Within the virtual construction site environment, it is possible to view and edit the project's role layers (Figure 10a). For example, a corroded structural plate can be identified and modified (Figure 10b); it may be replaced with another of similar dimensions (Figure 10c–f), according to the technical specifications provided in the "Material Technical Sheet" menu and as appropriate to the case. In addition, structural bolts can be added or removed based on the specific needs of the study.

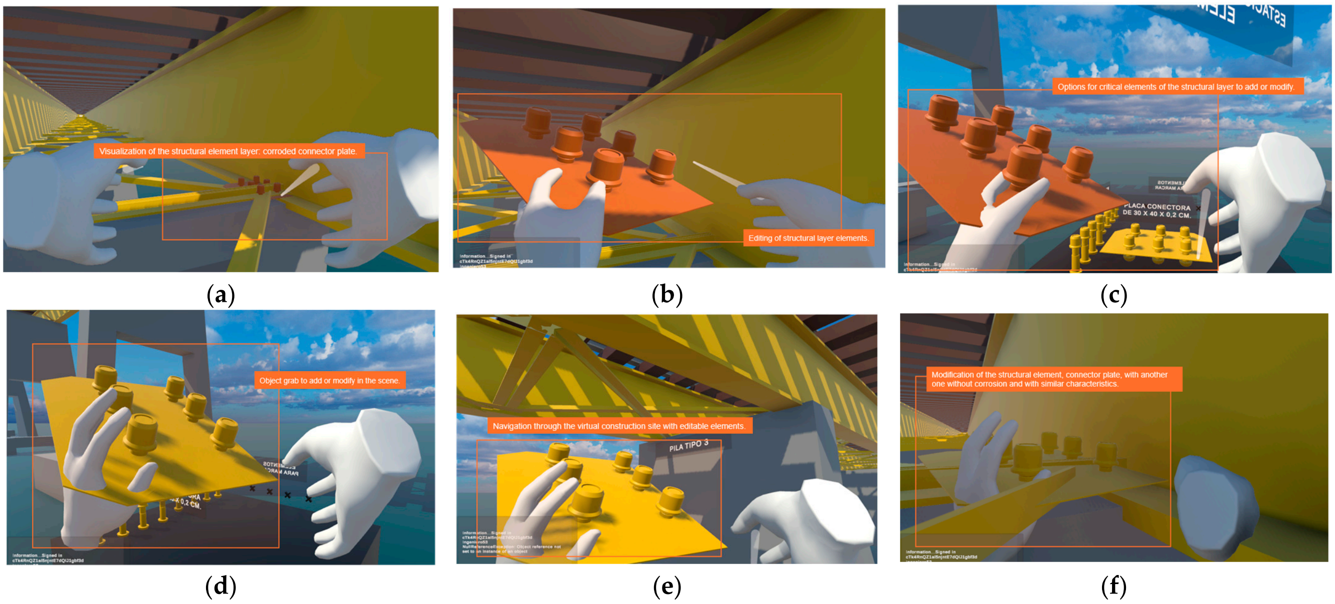



**Figure 10.** Functionalities of the Tool for Viewing and/or Editing the Project Role Layers. (**a**) Visualization of the structural element layer: corroded connector plate; (**b**) Editing of structural layer elements; (**c**) Options for critical elements of the structural layer to add or modify; (**d**) Object grab to add or modify in the scene; (**e**) Navigation through the virtual construction site with editable elements; (**f**) Modification of the structural element, connector plate, with another one without corrosion and with similar characteristics.

To support these tasks, the system includes useful features such as measurement tools (for both long and short distances), marking elements, a multi-user option allowing several users to participate simultaneously, and external functions such as screenshot capture via VR headset or PC, and collaborative meetings via Zoom or Google Meet (latest versions available at the time of the experiments, November–December 2023).

#### 5.3.7. Collaboration and Communication Across Different Geographic Locations

When starting the experience in multi-user mode, the session allows up to 20 project participants, regardless of their geographic location (Figure 11a,b). This enables the inspection and collaboration on the same project from anywhere in the world and in real time. Participants can simultaneously view each other's actions within the virtual construction site, facilitating collaboration and joint decision-making (Figure 11c–e).

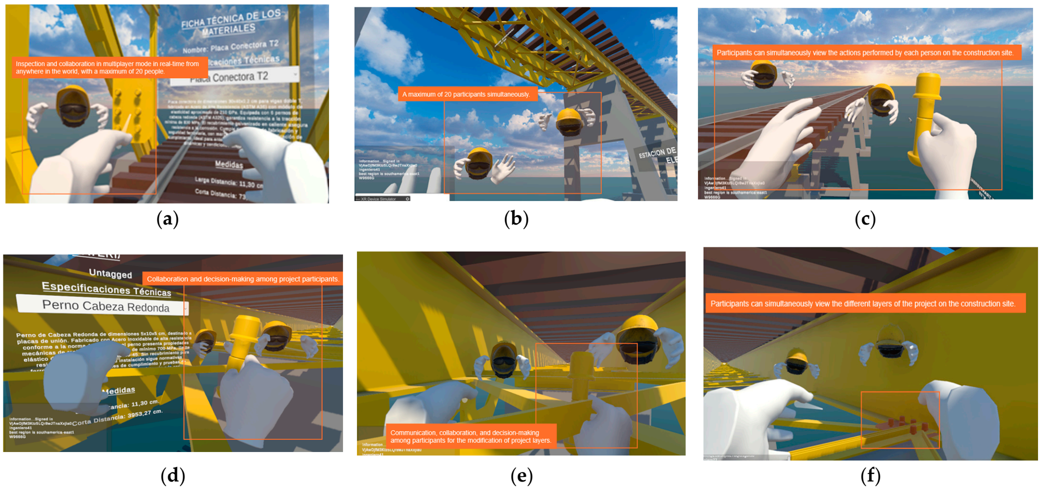



**Figure 11.** Functionalities of the Tool for Collaboration and Communication Across Different Geographic Locations. (**a**) Inspection and collaboration in multiplayer mode in real-time from anywhere in the world, with a maximum of 20 people; (**b**) A maximum of 20 participants simultaneously; (**c**) Participants can simultaneously view the actions performed by each person on the construction site; (**d**) Collaboration and decision-making among project participants; (**e**) Communication, collaboration, and decision-making among participants for the modification of project layers; (**f**) Participants can simultaneously view the different layers of the project on the construction site.

For example, users can work together to decide on the spacing of bolts in a diagonal joint (Figure 11f). They use marking tools to identify the points, measure the distance between them, make the necessary adjustments, and capture an image as a reference to solve the issue. By visualizing the changes at a 1:1 scale, all participants can assess how the object will appear in reality before making a final decision.

#### 5.3.8. BIMTable at the Construction Site and VR-Compatible Computer at the Engineering Office

The BIMTable is designed to operate in harsh environments such as construction sites, providing the necessary power to support various engineering projects, including plans, 3D models, and the implementation of Virtual Reality (VR). It also features a large screen that allows for simultaneous viewing by multiple team members when needed. Its specifications are adapted for use both at the actual construction site and in the engineering office (Figure 12a).


**Figure 12.** Functionalities of the BIMTable at the Construction Site and the VR-Compatible Computer at the Engineering Office. (**a**) BIMTable information hub; (**b**) VR-compatible computer in the engineering office.

In the case of the office, a physically robust device is not required; a computer that meets the technical specifications listed in Table 4 is sufficient to perform the same tasks (Figure 12b). Both technologies, being VR-compatible, are essential for connecting the engineering office with the actual construction site through collaborative meetings using the VR application.

5.3.9. BIMTable Linked to Virtual Reality (VR) for Simultaneous Work

The BIMTable integrates with Virtual Reality (VR) to enable simultaneous work with the engineering office (Figure 13a). This requires that the SteamVR software be installed and configured with an active session capable of detecting the VR equipment (HTC Vive: base stations, headset, and controllers; HTC Corporation, New Taipei City, Taiwan) prior to use (Figure 13b–d). Additionally, the same devices must be installed and ready for use both at the construction site and on the computer in the technical office. This ensures that the equipment is properly prepared and functional, avoiding delays during collaborative VR meetings.

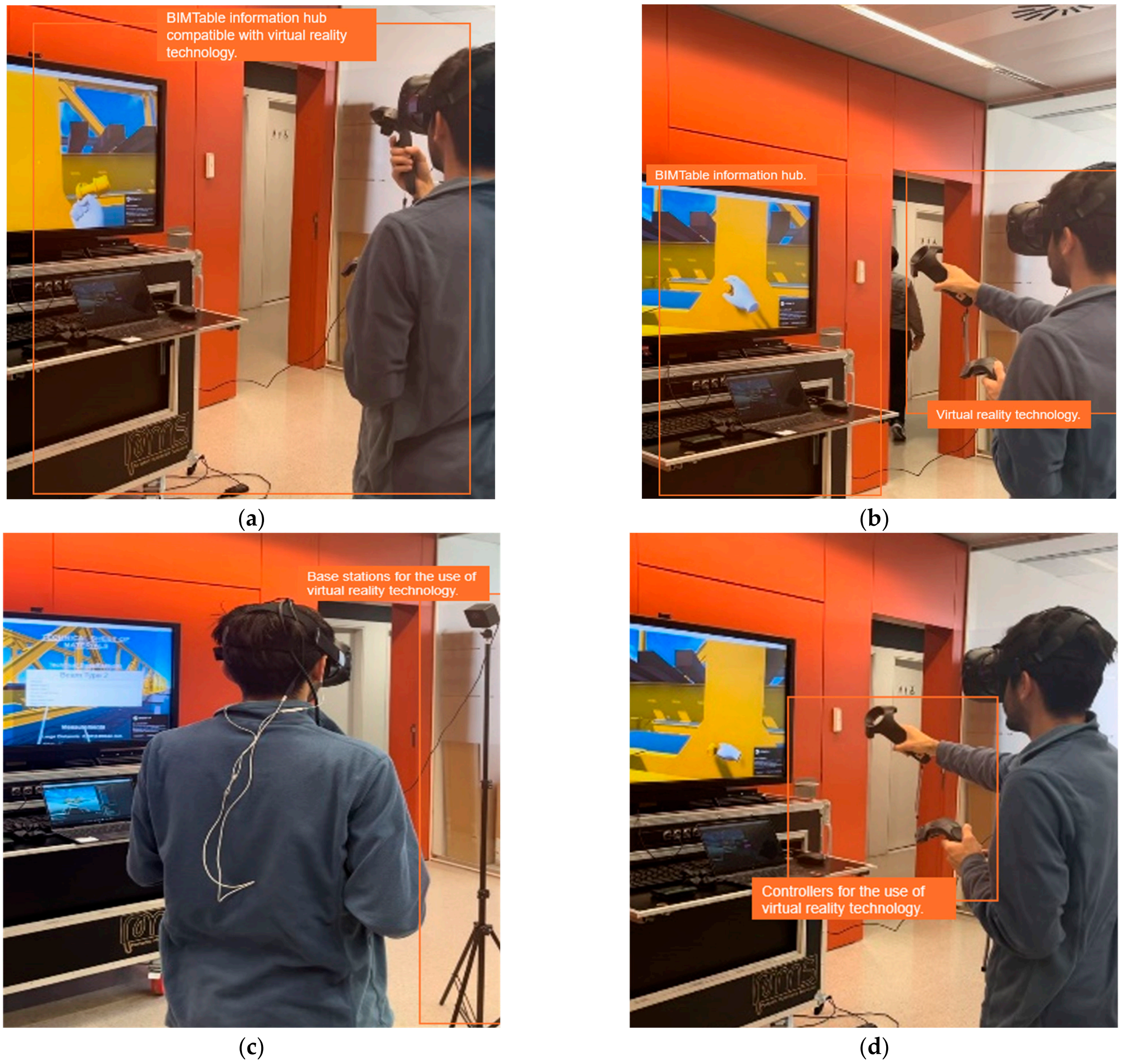



**Figure 13.** Functionalities of the Tool Linking the BIMTable to Virtual Reality (VR) for Simultaneous Work. (**a**) BIMTable information hub compatible with virtual reality technology; (**b**) BIMTable information hub and virtual reality technology; (**c**) Base stations for the use of virtual reality technology; (**d**) Controllers for the use of virtual reality technology.

# 6. Case of Study

## 6.1. Contextualization of the Case Study

The case study focuses on the inspection of a truss railway bridge, using a modified RFI communication workflow implemented in an application specifically designed for this structure, based on its BIM model in Virtual Reality. This bridge, located in Chile, is approximately 350 m long and features a mixed typology: its foundations, piers, and abutments are made of reinforced concrete, while its superstructure consists of a steel truss that replaced the original wooden spans (Figure 14).

**Figure 14.** Perspective view of the railway bridge showing the section without truss.

Currently, the bridge carries freight trains, and due to its age, inspections are crucial to ensure its continued functionality. Its structural typology and wear from prolonged use have led to corrosion and other damage, making access to certain areas during inspections difficult. Furthermore, its remote location over a river increases safety risks for workers, raises inspection costs, and poses logistical challenges.

The implementation of the modified RFI communication workflow in this context not only enables safer and more efficient inspections but also facilitates the effective resolution of identified issues, ensuring proper bridge maintenance and optimizing resources.

## 6.2. Contextualization of the Case Study Application

The objective of the case study was to evaluate the performance of the modified communication workflow through Requests for Information (RFIs), integrating Virtual Reality (VR) technology. Experts were first introduced to the current communication workflow between the construction site and the engineering office. A methodology was then applied, which included preliminary surveys (Expert Group Categorization and Perception Change with the VR Experience), a collaborative simulation using VR technology, and post-experience surveys (Communication, Perception Change with the VR Experience, User Experience, and Symptoms Associated with Technology Use). Participation was limited to six specialists, all of whom fully completed both questionnaires.

It is important to clarify that the case study corresponds to a simulation of an inspection scenario for an existing bridge. The five RFIs addressed during the simulation were based on real RFIs generated in similar steel bridge projects, ensuring that the technical challenges represented are aligned with actual industry practices. The simulated scenario replicates common accessibility difficulties, such as remote locations, bridges situated over bodies of water, and the need for significant travel time for inspection teams. In real inspections, safety risks may arise due to corroded structural elements, mobility restrictions caused by harness reach, and limitations in visibility or object manipulation due to the bridge’s condition. In the virtual environment, these limitations are overcome:

VR allows inspections to be conducted without physical presence on site, reducing travel time and associated costs, improving worker safety, and providing complete freedom of movement and visualization. Inspectors can virtually access, manipulate, or replace bridge components, thereby mitigating the physical and safety constraints inherent to on-site inspections.

During the experience, the participants, connected via Google Meet, interacted in real time: one recreated the construction site using the BIM Table and VR technology, while the evaluator simulated the engineering office using a compatible computer from a different geographical location. During the simulation, five RFIs from the case study were resolved, applying eight practices to mitigate communication barriers. The total duration of the experience was 40 min.

To assess their responses, a Dichotomous Scale was used (with two-point quantitative variables) [38], as well as a five-point Likert Scale to capture different degrees of opinion through qualitative variables [39] (Tables 5–13), allowing for the evaluation of the proposal's effectiveness. This workflow is illustrated in Figure 15 below.

**Table 5.** Dichotomous Scale. Adapted from [38].

| Associated Value | Qualitative Variable |
|---|---|
| 1 | Yes |
| 2 | No |

**Table 6.** Type A Likert Scale. Adapted from [39].

| Associated Value | Qualitative Variable |
|---|---|
| 1 | Very Low |
| 2 | Low |
| 3 | Intermediate or Neutral |
| 4 | High |
| 5 | Very High |

**Table 7.** Type B Likert Scale. Adapted from [39].

| Associated Value | Qualitative Variable |
|---|---|
| 1 | Very Vaguely |
| 2 | Vaguely |
| 3 | Indifferent or Neutral |
| 4 | Highly |
| 5 | Completely |

**Table 8.** Perception Change Questions After Experiencing Virtual Reality.

| N° | Expert Knowledge Level | Response Options |
|---|---|---|
| 1 | Before experiencing this and based on your knowledge, would you consider yourself resistant to implementing technologies such as Virtual Reality to mitigate communication barriers in construction projects? (Yes/No). If your answer was yes, how would you rate your level of resistance to implementing this technology? | (1) Very Low<br>(2) Low<br>(3) Intermediate<br>(4) High<br>(5) Very High |
| 2 | After experiencing this, would you consider yourself resistant to implementing this new Virtual Reality technology to mitigate the communication barriers that currently exist in construction projects? (Yes/No). If your answer was yes, how would you rate your level of resistance to implementing this technology? | |
| 3 | Before experiencing this, what would you say was your level of confidence with Virtual Reality software? | |
| 4 | After experiencing this, what would you say is your level of confidence with Virtual Reality software? | |

**Table 9.** Type (a) Communication Questions.

| N° | (a) Collaboration in the Virtual Reality Experience | Response Options |
|---|---|---|
| 1 | How would you rate this experience in terms of collaborative work? | (1) Very Low<br>(2) Low<br>(3) Intermediate<br>(4) High<br>(5) Very High |
| 2 | How would you rate this experience in terms of collaborative work compared to current collaborative practices? | |
| 3 | How would you rate the ease of resolving RFIs and making decisions using the Virtual Reality experience? | |

**Table 10.** Type (b) Communication Questions.

| N° | (b) Current vs. Proposed Communication Workflow Between Construction Site and Engineering Office for the Resolution of Each RFI | Response Options |
|---|---|---|
| 1 | To what extent do you believe that this Virtual Reality experience, combined with baseline knowledge of methodologies currently used in the AEC industry such as Lean Construction and BIM, fulfills the objective of mitigating the communication barriers identified at the beginning of the experience? | (1) Very Low<br>(2) Low<br>(3) Intermediate<br>(4) High<br>(5) Very High |
| 2 | To what extent do you believe this Virtual Reality experience provides a solution to the Request for Information (RFI)? | |
| 3 | After experiencing this, how would you rate the efficiency of the current workflow used to resolve this RFI? | |
| 4 | How would you rate the efficiency of the proposed workflow for resolving this RFI while mitigating communication barriers? | |
| 5 | How would you evaluate the proposed practices within the immersive environment for mitigating communication barriers? | |
| 6 | For this type of Request for Information (RFI), would you choose the proposed workflow from this experience over the currently existing workflow? | Yes/No |

**Table 11.** Type (c) Communication Questions.

| | (c) CB/Practices | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | Question/Response Option |
|---|---|---|---|---|---|---|---|---|---|---|
| (a) | Unclear Objectives and Lack of Trust | | ✓ | ✓ | | | | | | To what extent do you believe these indicated practices, combined with foundational knowledge of Lean Construction and BIM, can mitigate these communication barriers?<br>(1) Very Low<br>(2) Low<br>(3) Intermediate<br>(4) High<br>(5) Very High |
| (b) | Limited Resources, Unclear Communication Channels, and Political/Community Interference | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| (c) | Information Filtering | | ✓ | | | | | | | |
| (d) | Ineffective Notification System | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | |
| (e) | Language Difficulties | ✓ | ✓ | ✓ | ✓ | | ✓ | | | |
| (f) | Poor Listeners | | ✓ | ✓ | ✓ | | | ✓ | ✓ | |
| (g) | Conflicting Cultural Values | ✓ | ✓ | ✓ | ✓ | | | | | |
| (h) | Lack of Necessary Skills | | ✓ | ✓ | ✓ | ✓ | | | | |

Note: The check marks (✓) indicate the relationship used in the evaluation form between the proposed practices and the communication barriers. They represent the question: to what extent do you think these practices, together with the current LC and BIM tools, help mitigate the identified communication barriers?

**Table 12.** User Experience.

| N° | Statement | Response Option |
|---|---|---|
| 1 | I feel that it is a comfortable experience to use | Check the box if the respondent identifies with any of these statements |
| 2 | I feel that it is an easy experience to use | |
| 3 | I feel that it is an easy experience to implement | |
| 4 | I feel that it is a reliable experience | |
| 5 | It provides better visualization of the overall scenario | |
| 6 | I felt safe inspecting any part of the bridge | |

**Table 12.** *Cont.*

| N° | Statement | Response Option |
|---|---|---|
| 7 | It has advantages over a real-life inspection | |
| 8 | It is highly valuable for collaboration among roles | |
| 9 | It is highly valuable for ensuring participant safety | |
| 10 | It is highly valuable due to the ability to perform it from any geographic location | |
| 11 | It was easy for me to adapt to the Virtual Reality technology | |
| 12 | I can make decisions based on what I experienced in Virtual Reality | |
| 13 | I need more time to adapt to Virtual Reality technology | |
| 14 | It helped me better understand certain aspects | |
| 15 | I feel satisfied with the Virtual Reality experience | |

**Table 13.** Symptoms Associated with the Use of VR Technology. Adapted from [40].

| N° | Symptoms | Response Option |
|---|---|---|
| 1 | Nausea | Check the box if the respondent identifies with any of these statements |
| 2 | Sweating | |
| 3 | Dizziness | |
| 4 | Headache | |
| 5 | Eye Fatigue | |
| 6 | Blurred Vision | |
| 7 | Difficulty Concentrating | |
| 8 | Loss of Balance | |
| 9 | Disorientation | |
| 10 | General Discomfort | |
| 11 | Other | |
| 12 | None | |

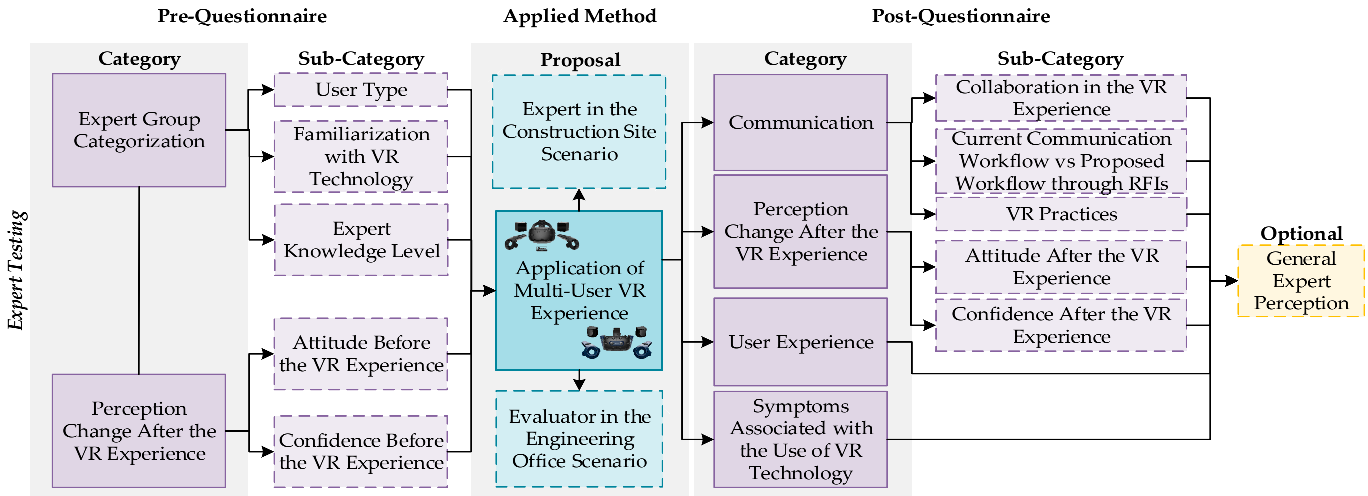



**Figure 15.** Collaborative Meeting Simulation with the Proposed Communication Workflow Between Construction Site and Engineering Office.

Based on the types of RFIs identified in the referenced research, five RFI situations that arose during the inspection process have been selected for analysis (Table 14).

Consequently, to carry out the analysis of each situation and type of RFI, the process begins by evaluating which communication barrier each one corresponds to (Table 15).

**Table 14.** RFIs Identified During the Inspection Process of the Railway Bridge. Adapted from [1].

| Code | Situation | RFI Type |
|---|---|---|
| S1 | "Does the connector plate for axis A between diagonal joints 13 and 14, located between transverse axes No. 18 and 19, exist? Although it is represented in the structural plan along with its respective bolts, it has not been found on site. We would appreciate clarification on this information." | Information Clarification—Conflict |
| S2 | "Clarification is requested regarding the specific concrete strength conditions for the piers of the truss railway bridge. Additional details are needed on the recommended concrete mixes, applicable strength tests, and any particular requirements we should consider during construction." | Information Clarification—Insufficient |
| S3 | "On transverse axis No. 25 at axis B, a completely corroded connection plate has been detected. It is proposed to replace it with one of similar dimensions 30 × 40 × 0.2 cm, and approval is requested to proceed with this change. Images are attached." | Approval |
| S4 | "At diagonal joint 5 between the beams of piers 2 and 3, a discrepancy was detected: only 2 of the 4 bolts indicated in the structural plan have been installed. Due to site conditions, an alternative design solution is requested to ensure structural integrity. Thank you for your prompt attention to this matter." | Alternative Design Solution |
| S5 | "Initially, anti-corrosive paint was to be applied only to connections on transverse axes 1 to 8 and 20 to 25 due to greater exposure. However, as more severe deterioration was observed in the connections of transverse axes 9 to 22, the strategy was adjusted to focus exclusively on these affected areas. A reinforcement layer will be added to critical areas such as joints." | Other |

**Table 15.** Classification of the RFI According to the Communication Barriers (CB) to Which It Belongs.

| RFI/BC | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 | B10 | B11 | B12 | B13 | B14 | B15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | | | | ✓ | | ✓ | ✓ | | ✓ | | | ✓ | | | |
| S2 | | | | ✓ | | ✓ | ✓ | | ✓ | | | | | | |
| S3 | | | | | | | ✓ | ✓ | | | | | | | |
| S4 | | | | ✓ | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | |
| S5 | | | | | | | ✓ | ✓ | ✓ | | | | | | |

Note: The check marks (✓) indicate the relationship between each RFI situation analyzed and the communication barrier to which it corresponds.

With the knowledge of the Communication Barriers (CB) involved in each challenge, a match is made with Table 2. The proposed solution must comprehensively address all these aspects in order to achieve an effective outcome. Finally, a summary of the distances affected in each situation is obtained, followed by a guide to address the specific solutions for each case (Table 16).

The communication barriers (CB) in each situation were analyzed, and based on Distance Theory, eight practices are proposed for implementation in Virtual Reality (VR) environments combined with the BIMTable. These practices, designed to complement Lean Construction (LC) and Building Information Modeling (BIM), aim to effectively mitigate communication barriers in construction projects (Table 17).

**Table 16.** RFI Situations Evaluated Based on Distance Theory.

| RFI | RFI Type | Communication Barriers | Distances |
|---|---|---|---|
| S1 | Information Clarification—Conflict Information | B4, B6, B7, B9, B12 | D1, D2, D3, D4, D6, D7, D8 |
| S2 | Information Clarification—Insufficient Information | B4, B6, B7, B9 | D1, D2, D3, D4, D6, D7, D8 |
| S3 | Approval | B7, B8 | D1, D2, D4, D5, D7, D8 |
| S4 | Alternative Design Solution | B4, B7, B8, B9, B10, B12 | D1, D2, D3, D4, D5, D6, D7, D8 |
| S5 | Other | B8, B9 | D1, D2, D3, D4, D5, D7, D8 |

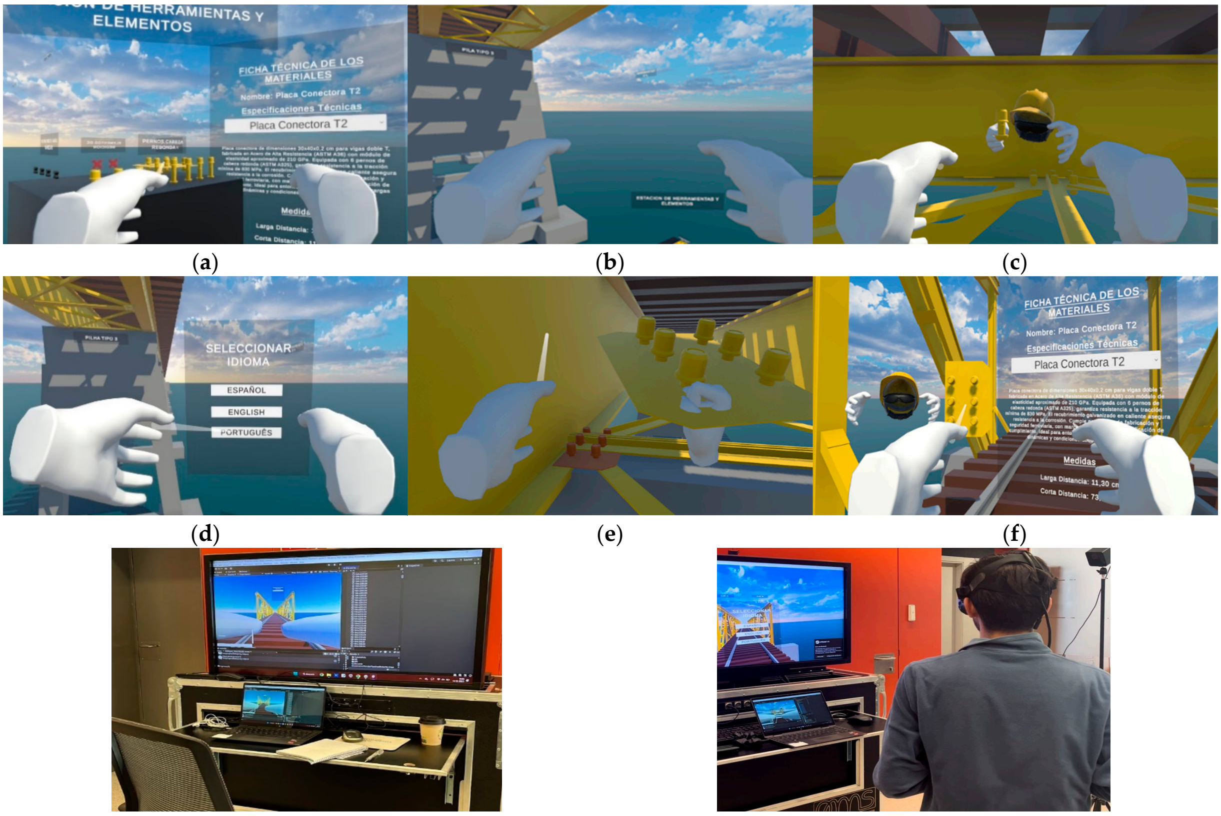
**Table 17.** Practices in VR/BIM Table Based on Distance Theory.

| Practices in RV/BIMTable | Description | Distance That Mitigates |
|---|---|---|
| 1. Visualization and audio playback by project participants of the characteristics and technical specifications of construction materials while interacting with them in an immersive virtual scenario. | VR helps project participants understand the differences between material options by interacting with them. | Semantic Distance |
| 2. Virtual walkthrough of the construction site by project participants, identifying the construction location, site position, and material and project element information in visual and audio formats. | VR helps participants better understand the full context of the construction site through a virtual walkthrough in which they interact with elements, improving comprehension of the project's objectives. | Cognitive Distance |
| 3. Real-time voice communication and collaboration between project participants in an immersive virtual environment. | VR helps resolve a large percentage of doubts during collaborative design reviews, simulations, training sessions, or remote walkthroughs—minimizing misunderstandings and missing information. This practice enables greater client satisfaction and stronger project design engagement. | Cognitive Distance |
| 4. Interaction with project element information and communication between project participants in their preferred language. | VR allows participants to interact with construction elements—reading and hearing material and component information in their chosen language—and supports instant translation of communication between participants. | Cognitive Distance |
| 5. Visualization and/or editing of layers related to the different project roles. | VR enables better project comprehension by offering stereoscopic visualization of design clashes before decisions are made. Compared to static 3D model images, this practice supports faster, more efficient collaborative design reviews, training, and virtual simulations. | Cognitive Distance |
| 6. Collaboration and communication among project participants within a 3D-modeled virtual scenario from different geographic locations. | VR enables participants to communicate and collaborate from locations other than the construction site within the same 3D-modeled virtual environment, fostering remote collaboration. | Geographical Distance |
| 7. The BIM Table is located at the construction site, and a VR-compatible computer is located in the engineering office. These systems maintain communication and host a shared cloud of updated construction project documents accessible to all participants. | The BIM Table facilitates communication between the construction site and the engineering office for resolving RFIs and stores updated project data and documents, accessible to participants for collaborative purposes. | Navigational Distance |
| 8. The BIM Table is connected with Virtual Reality (VR) for simultaneous collaboration. | VR, combined with the BIM Table, helps reduce the time needed to resolve RFIs by eliminating iterations in the current communication process between the site and engineering office. It also saves time in virtual meetings, as updated project documents are available in the BIM Table's shared cloud. | Temporal Distance |

The virtual construction site, along with the practices in VR/BIMTable, are illustrated in Figures 16 and 17, respectively.

(**a**) (**b**)

**Figure 16.** Case Study Project: Railway Bridge Over Water. (**a**) Truss Railway Bridge Project viewed from below, East side, showing a tools and elements station from the Case Study; (**b**) Truss Railway Bridge Project viewed from above, on top of the bridge, showing some of its elements.

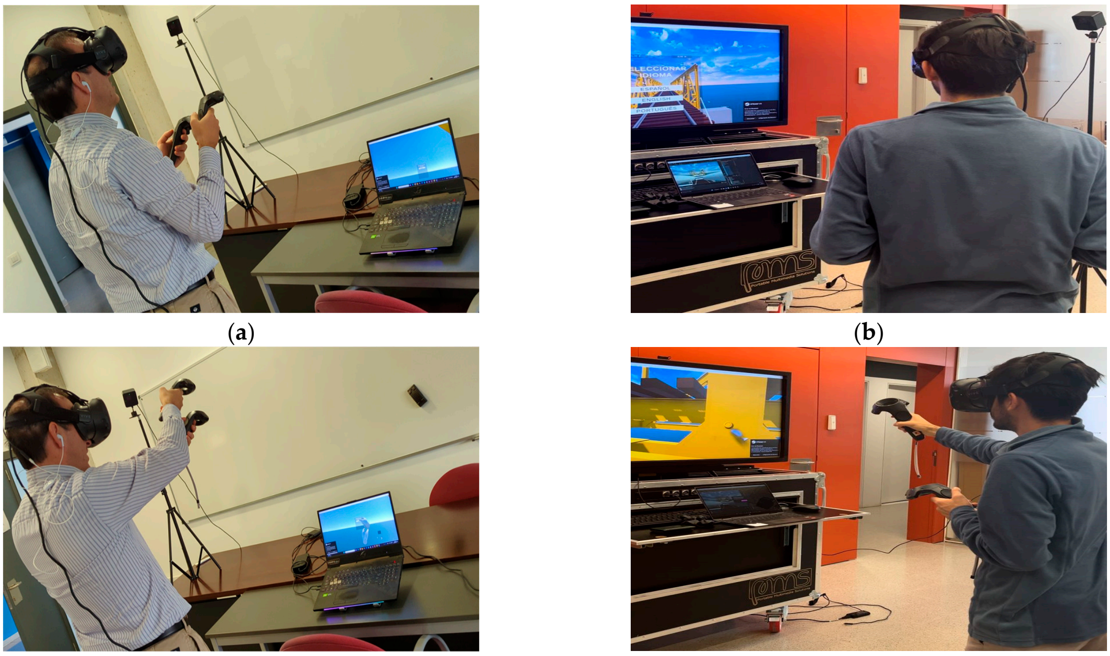



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**) (**h**)

**Figure 17.** Practices in VR/BIMTable Based on Distance Theory in the Virtual Construction Site Scenario of the Project. (**a**) Visualization and Audio Playback of Technical Specifications; (**b**) Virtual Walkthrough of the Virtual Construction Site; (**c**) Real-Time Voice Communication and Collaboration; (**d**) Interaction with Project Information and Communication in Preferred Language; (**e**) Viewing and/or Editing the Project Role Layers; (**f**) Collaboration and Communication Across Different Geographic Locations; (**g**) BIM Table at the Construction Site and VR-Compatible Computer at the Engineering Office; (**h**) BIM Table Linked to Virtual Reality (VR) for Simultaneous Work.

In the real-life case study, communication between the construction site and the engineering office using the modified workflow can be seen in Figure 18 below.

The Organizational, Psychological, and Adherence Distances are not directly addressed in this research, as they are considered to be better handled through Lean Construction (LC). These distances are related to complex communication barriers such as poor leadership, ethical conflicts, religious issues, and age differences, which require more specific approaches.



(**a**) (**b**) (**c**) (**d**)

**Figure 18.** Collaborative Meeting Simulation with the Proposed Communication Workflow Between Construction Site and Engineering Office. (**a**,**c**) Collaborative Meeting Simulation in the Engineering Office with a Laptop with the Specified Specifications, Where the Virtual Reality Technology Devices Are Identified: Sensors with Base Stations, HTC Vive Virtual Reality Headset, and Controllers; (**b**,**d**) Collaborative Meeting Simulation at the Construction Site with BIM Table with the Specified Specifications, Where the Virtual Reality Technology Devices Are Identified: Sensors with Base Stations, HTC Vive Pro 2 Virtual Reality Headset, and Controllers (HTC Corporation, New Taipei City, Taiwan).

In this study, the focus is on mitigating the remaining 11 barriers through practices designed to address each RFI situation. These practices work together to effectively reduce communication barriers, and their specific implementation for each case is represented through the application of the 8 proposed practices (Tables 18 and 19). This approach focuses on improving communication in the identified critical situations.

**Table 18.** VR/BIMTable Practices to Mitigate Communication Barriers Based on Distance Theory.

| N° | Distance | Practice | Communication Barrier Mitigated |
|---|---|---|---|
| 1 | Semantic | (a) 2, 3, 4 y 6 | B14 |
| | | (b) 2, 3 y 4 | B5 |
| 2 | Cognitive | - | B9 |
| 3 | Cognitive | 2 | B4, B12 |
| 4 | Cognitive | (a) 1, 2, 3 y 6 | (a) B14 |
| | | (b) 2, 3, 7 y 8 | (b) B2 |
| | | (c) 1, 2 y 3 | (c) B5 |
| 5 | Cognitive | (a) 2, 3 y 4 | (a) B11 |
| | | (b) 1, 2, 3, 4, 6, 7 y 8 | (b) B7 |
| 6 | Geographical | (a) 2, 3, 4, 5, 7 y 8 | (a) B6, B8, B1 |
| | | (b) 1, 2, 3 y 4 | (b) B14 |
| 7 | Navigational | 2, 3, 4, 5, 6 y 8 | B6, B8, B1 |
| 8 | Temporal | 2, 3, 4, 5, 6 y 7 | B6, B8, B1 |

**Table 19.** Practices that Mitigate the Communication Barriers (CB) of the RFIs Under Study.

| RFI Code | RFI Type | Communication Barrier | Distance | VR/BIMTable Practice |
|---|---|---|---|---|
| S1 | Information Clarification—Conflict | B4, B6, B7, B9, B12 | D1, D4, D7, D8 | Practices 1, 2, 3, 4, 5, 6, 7, and 8—Semantic, Cognitive, Geographical, Navigational, and Temporal Distances. |
| | | | *D2, D3, D6* | |
| S2 | Information Clarification—Insufficient | B4, B6, B7, B9 | D1, D4, D6, D7, D8 | |
| | | | *D2, D3* | |
| S3 | Approval | B7, B8 | D1, D4, D6, D7, D8 | |
| | | | *D2, D5* | |
| S4 | Alternative Design Solution | B4, B7, B8, B9, B10, B12 | D1, D4, D6, D7, D8 | *Current Methodologies and Tools from Lean Construction and Building Information Modeling.* |
| | | | *D2, D3, D5* | |
| S5 | Other | B7, B8, B9 | D1, D4, D6, D7, D8 | |
| | | | *D2, D3, D5* | |

Note: Distances in italics (e.g., D2, D3, D6) indicate those considered to be better addressed and mitigated through the current methodologies and tools of Lean Construction (LC) and Building Information Modeling (BIM).

The combination of VR and the BIMTable proves to be effective in mitigating communication barriers and resolving RFIs in situations that require advanced visualization and complex decision-making. These include cases such as "Approval", "Alternative Design Solution", and "Questionable or Conflicting Information", where immersive collaboration improves access to complicated areas, such as inspections under a bridge over water, optimizing time, costs, and key decisions. However, in simpler cases like "Insufficient Information" or "Other", where an email would suffice, the implementation of immersive technology is not efficient or aligned with the project's objectives.

The proposal identifies an effective workflow for complex situations, improving remote collaboration and reducing communication barriers. The validation of these proposals will include expert evaluation of the VR experience, which will be addressed in the next section.

## 7. Validation of the Virtual Reality Experience as Part of the Proposed Workflow to Improve Communication Between Construction Site and Engineering Office

Six experts participated in the validation of the VR experience, which simulated a collaborative meeting between the site manager and the technical office manager for the railway bridge project. The objective was to resolve the 5 RFIs under study, applying the proposed practices in an immersive environment to mitigate communication barriers (CB) in each situation.

The data collection for this validation was carried out through surveys conducted in two phases: one before the experience and another immediately after. All participants completed both stages in full, with no need to exclude any responses. The design of these surveys incorporated elements that allowed for cross-checking and validating the consistency of the experts' responses. The complete set of questions used is presented in the (Tables 5–13), providing transparency and enabling the replicability of the process.

In the context of the following responses, the median is used as the representative measure, with a reference value of (3) "Intermediate/Neutral". Higher values suggest a positive response: (4) High, (5) Very High, while lower values indicate a negative response in that area: (1) Very Low and (2) Low.

## 7.1. Categorization of the Expert Group

To carry out the validation of the virtual reality experience, a group of 6 professionals was selected, all sharing the common characteristic of being experts in at least one of the following categories: (1) Bridge Expert, (2) Construction Expert, (3) Communication Expert, and (4) Virtual Reality Expert. The possibility of being a hybrid expert, i.e., possessing knowledge in more than one area, was also allowed (Figure 19).

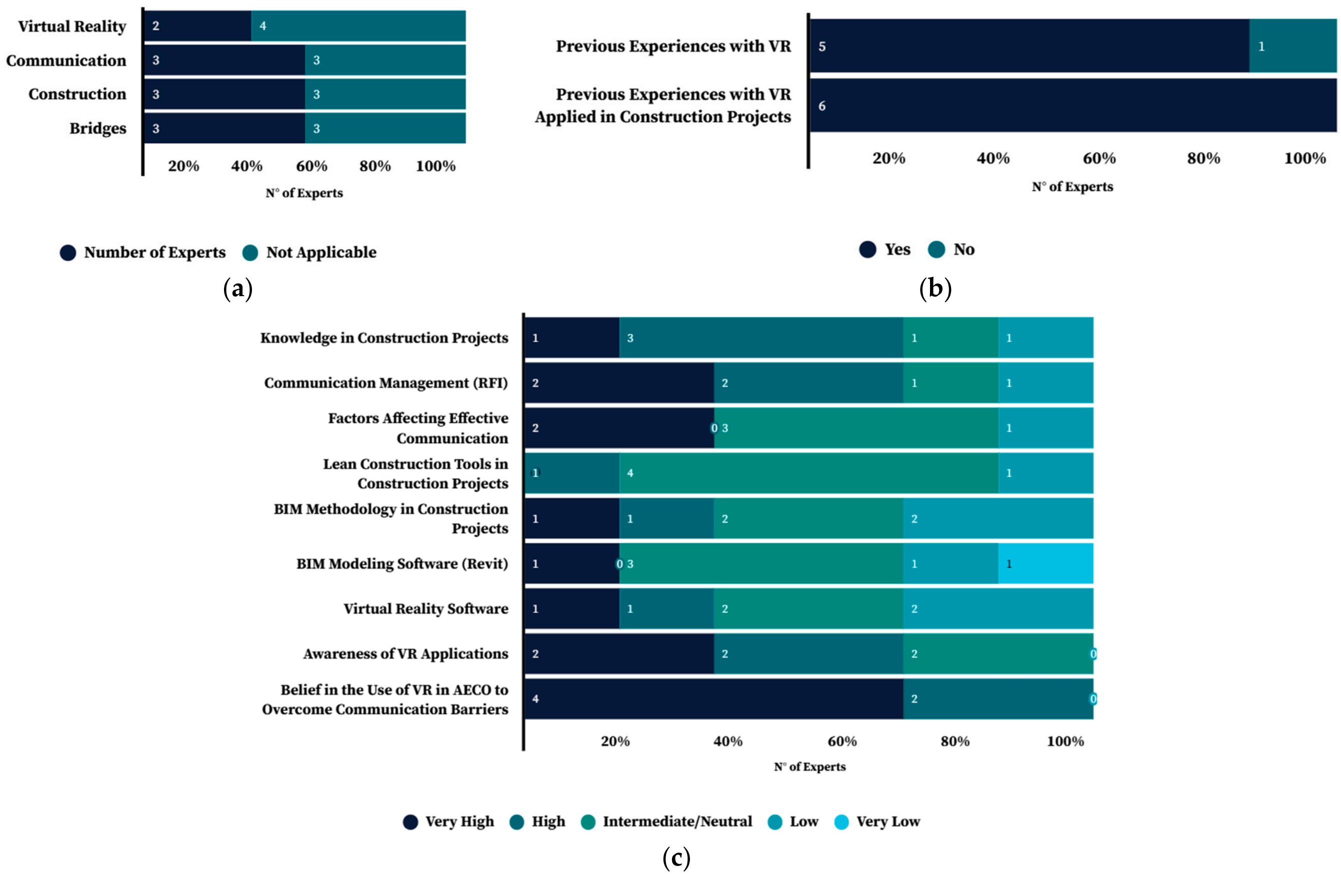



**Figure 19.** Categorization of the Expert Group. (**a**) User Type; (**b**) Familiarization with Virtual Reality Technology; (**c**) Expert Knowledge Level.

The evaluation involved 6 experts: 3 bridge experts, 3 construction experts, 3 communication experts, and 2 virtual reality experts. The majority showed high or very high levels of knowledge in construction project topics, communication management (such as RFIs), and VR applications in the AICO industry, highlighting its potential to overcome communication barriers (CB).

Solid levels were also identified in intermediate topics, such as factors affecting effective communication, use of Lean Construction (LC), and BIM management. No low levels were recorded in any of the evaluated topics. Regarding familiarity with VR technologies, participants had previous experience: 5 out of 6 had worked with VR in construction projects before this evaluation, which strengthens the validity of the obtained results.

## 7.2. Change in Perception from Experiencing Virtual Reality

Two identical questions were formulated both before and after the experience to identify variations in their perspective on the willingness to adopt this technology as a tool to mitigate communication barriers (CB) in construction projects. The responses were classified as: "Yes," indicating a negative attitude of resistance to implementation, and "No," indicating a positive attitude toward the same topic (Figure 20).

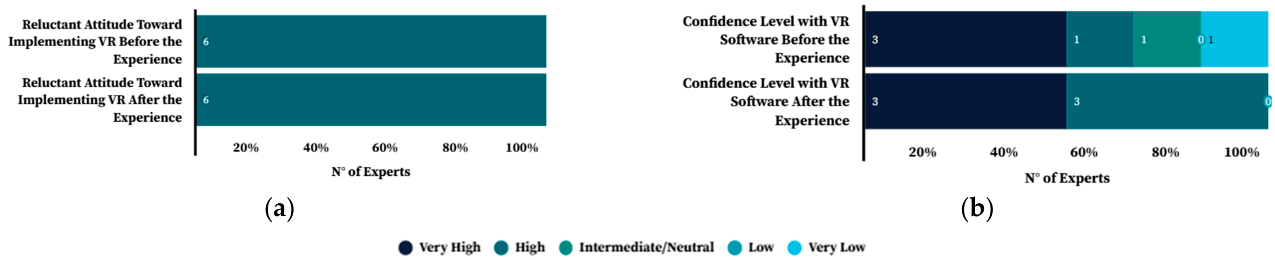



**Figure 20.** Change in Perception from Experiencing Virtual Reality. (**a**) Attitude: Expert's attitude towards implementing Virtual Reality technology to mitigate the communication barriers currently present in construction projects. (**b**) Confidence: Expert's level of confidence with VR software.

The results in category (a) Attitude show that there was no variation before and after the experience, as all experts responded with a "No" in both situations, indicating a positive attitude toward the implementation of Virtual Reality technology for mitigating communication barriers in construction projects at all times. Regarding (b) Confidence, the results show a shift in the experts' perspective towards a higher level of confidence in Virtual Reality software after the experience, from an average of 3.8 (between "Intermediate/High") to an average of 4.5 (between "High/Very High"), which confirms a positive change in confidence towards VR software (Unity, version 2022.3.10f, together with SteamVR, version 2.2).

### *7.3. Teamwork Qualities in the VR Experience*

The goal is to determine whether the VR experience, by enabling communication and the implementation of collaborative practices, provides a higher level of collaborative work compared to current collaborative practices, ease in resolving RFIs, and decision-making (Figure 21).

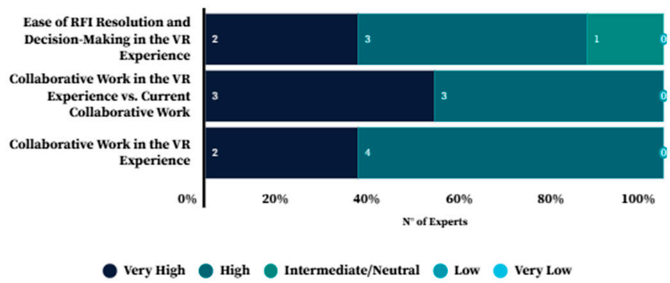



**Figure 21.** Teamwork Qualities in the VR Experience.

The median of the evaluation is 4 ("High"), with the majority of evaluation results above the neutral level, indicating that collaborative work in the VR experience has a value beyond the intermediate level. In comparison to current collaborative work, a higher level is exhibited, with a median of 4.5 (between "Very High/High"). This shows a positive and superior evaluation of the work performed with the proposed communication workflow over the current workflow. Regarding the ease of resolving RFIs and decision-making in the virtual reality experience, it is positively evaluated with a value above the intermediate level, resulting in a median of 4 ("High"), suggesting that these actions can be carried out effectively and at a high level within the experience.

### *7.4. Characteristics of the Proposed Communication Workflow*

The questions evaluated the resolution of five RFIs within a VR environment, considering whether the experience meets the objective of mitigating communication barriers (CB), the perceived effectiveness in resolving RFIs, the comparison of efficiency between the current and proposed workflows, and the perception of the practices implemented in VR to mitigate barriers. The respondents expressed their preference between the two workflows, evaluating whether the proposed workflow is more effective in resolving RFIs and addressing communication barriers (Figure 22).

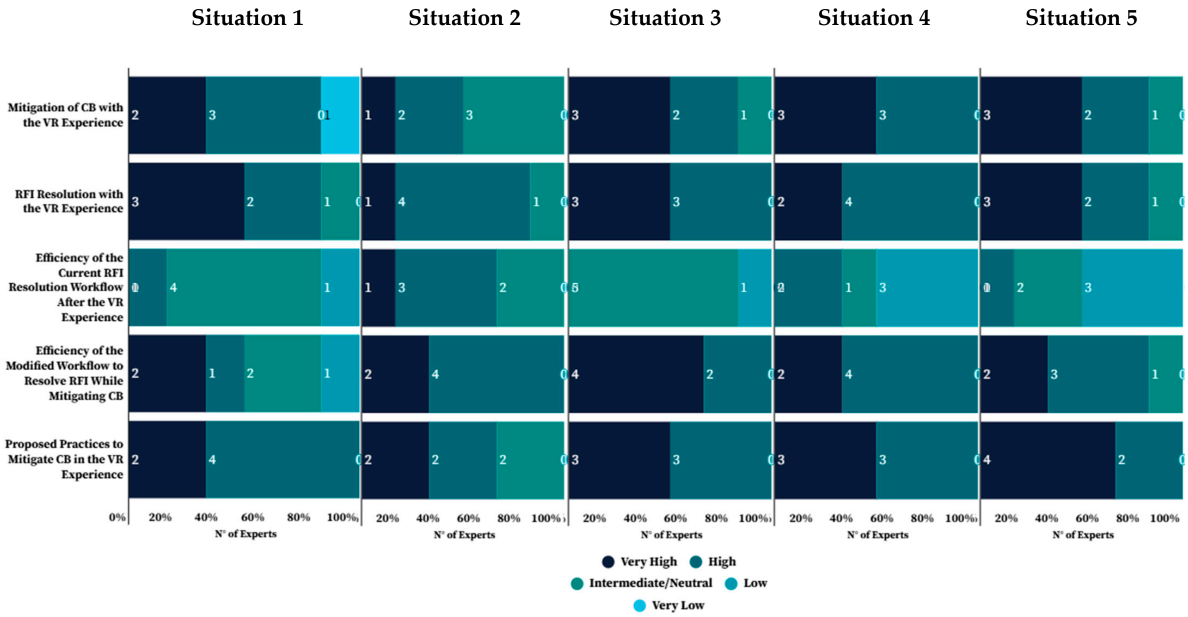



**Figure 22.** Characteristics of the Proposed Communication Workflow for Each RFI.

The results of the five evaluated RFI situations highlight the positive impact of VR in mitigating communication barriers (CB) and in resolving the RFIs. The detailed results of each situation are presented in Table 20.

**Table 20.** Result of the VR Experience Validation for Request for Information (RFI).

| RFI Classification/Subclassification | Results |
|---|---|
| Approval/NA [1] | The results for Situation 3—Approval RFI show that the Virtual Reality (VR) experience was effective in mitigating communication barriers, with an average rating of 4.3, reflecting a positive evaluation above the intermediate level. The resolution of the Request for Information (RFI) also achieved outstanding results, with an average of 4.5, highlighting the effectiveness of the VR experience in this context. In contrast, the current RFI resolution workflow received a neutral to negative evaluation, with an average of 2.8, indicating limited efficiency. The proposed workflow, on the other hand, showed significant improvement, with an average of 4.7 and unanimous preference from the experts, who highly valued its implementation. The proposed practices for mitigating communication barriers were rated positively, with an average of 4.5, confirming their success. All experts unanimously preferred the proposed workflow over the current one. |
| Alternative Design Solution/NA [1] | The results for Situation 4—Alternative Design Solution RFI demonstrate that the VR experience was effective in mitigating communication barriers, with an average of 4.3 and a median of 4.5, indicating a clearly positive evaluation. VR also provided an effective solution to the RFI, with similarly high scores compared to the intermediate level. In contrast, the current workflow received a neutral or negative rating, with an average of 2.7, indicating low to moderate efficiency. The proposed workflow was rated positively, with an average of 4.2, indicating clear improvement over the current process. The immersive practices to mitigate communication barriers were highly rated, averaging 4.7, reinforcing their effectiveness. Finally, expert preference was unanimous in favor of the proposed workflow, with all evaluators opting for its implementation to resolve this RFI. |
| Information Clarification/Conflict | The results for Situation 1—Conflict-related Information Clarification RFI suggest that the VR experience had a positive impact both on mitigating communication barriers and on resolving the RFI. In terms of communication barrier mitigation, the evaluation was favorable with an average of 3.8, while the RFI resolution via VR was rated even higher at 4.3, above the neutral level. However, the current workflow remained at an intermediate level, showing no improvement. In contrast, the proposed workflow showed slightly more positive results with an average of 3.7, offering only a modest advantage. The proposed immersive practices were positively evaluated with an average of 4.3, indicating their effectiveness in mitigating communication barriers. Expert preference leaned clearly toward the proposed workflow, with a 5 to 1 ratio in favor of its implementation over the current one for this RFI. |

**Table 20.** *Cont.*

| RFI Classification/Subclassification | Results |
| --- | --- |
| Information Clarification/Insufficient | The results for Situation 2—Insufficient Information Clarification RFI show that the VR experience had a positive impact on communication barrier mitigation, with an average evaluation between "Intermediate" and "High" (3.7), although with limited advantage over the neutral level. As for resolving the RFI, the outcome was clear, with an average of 4.0, indicating a positive evaluation above the intermediate level. The current workflow was also evaluated favorably, with an average of 3.8, suggesting that it is effective for handling this type of RFI. However, the proposed workflow stood out even more, with an average of 4.3, indicating improved performance. The proposed practices to mitigate communication barriers were well evaluated, with an average of 4.0, reinforcing their effectiveness. Finally, expert preference was strong in favor of the proposed workflow, with a 5 to 1 ratio compared to the current process. |
| Other/NA [1] | The results for Situation 5—Other RFI types show that the VR experience was effective in mitigating communication barriers, with an average of 4.5, indicating a clearly positive impact above the intermediate level. Likewise, resolving the RFI through VR was positively evaluated, with an average of 4.3, confirming its effectiveness. In contrast, the current workflow received a negative evaluation, with an average of 2.8, indicating low or neutral efficiency. The proposed workflow showed improvement, with an average of 3.7, indicating a higher level than the current process. The immersive practices for mitigating communication barriers were rated positively, with an average of 4.5, reinforcing their success. Finally, expert preference was unanimous in favor of the proposed workflow, with all evaluators choosing its implementation over the current one to resolve this RFI. |

[1] NA = No Applicable.

In general, the proposed VR-based workflow proved to be more effective and efficient in most situations, reducing communication barriers (CB) and improving RFI resolution, with a clear preference from the experts for its implementation.

### 7.5. Proposed VR Practices to Mitigate Communication Barriers (CB)

These results aim to determine the level of mitigation of the identified communication barriers (CB) using the proposed VR practices (Figure 23).

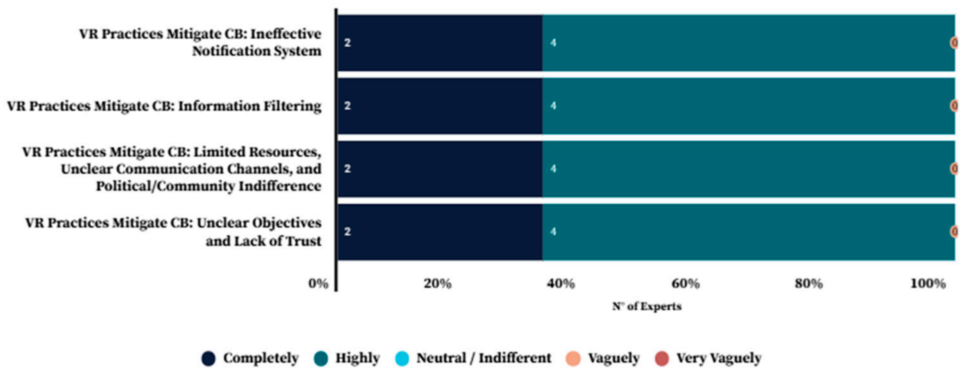



**Figure 23.** Proposed VR Practices to Mitigate Communication Barriers (CB).

In each of the four questions, all data points are positive, with 2 values for "Very High" and 4 for "High", resulting in an average of 4.3, which is between "High" and "Very High", and a median of 4 ("High"), yielding a positive evaluation. These results support the notion that the developed practices have had a positive impact on mitigating communication barriers (CB) and are rated at a higher level compared to a "Intermediate/Neutral" value, specifically addressing challenges related to unclear objectives, lack of trust, limited resources, ambiguous communication channels, political/community interference, information filtering, and an ineffective notification system.

### 7.6. User Experience

The goal is to determine the comfort and perception of the user when using the construction site experience through virtual reality technology (Figure 24).

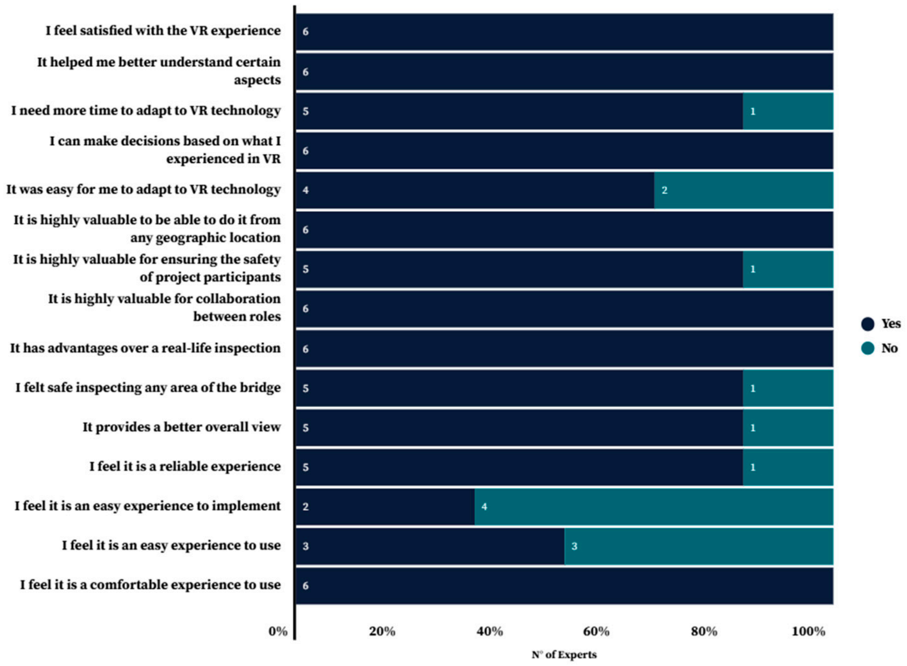



**Figure 24.** User Experience.

All participants expressed satisfaction with the VR experience, highlighting its usefulness for decision-making, multi-user collaboration from any location, and advantages over real inspections, especially in terms of safety and visualization.

However, 83.33% indicated needing more time to adapt to the technology, while 66.67% felt it was easy to adapt. Additionally, 50% considered the experience easy to use, and 33.33% highlighted its ease of implementation.

### *7.7. Symptoms Associated with the Use of VR Technology*

To carry out this evaluation, the symptoms established in the SSQ (Simulator Sickness Questionnaire) were used, which is employed to assess and describe simulator discomfort (Figure 25).

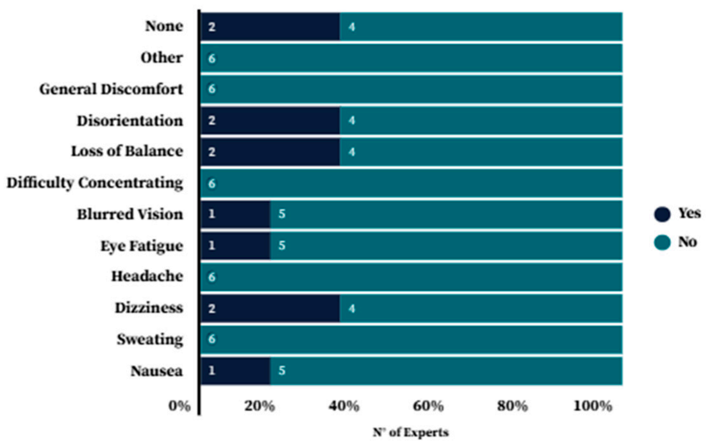



**Figure 25.** Symptoms Associated with the Use of VR Technology.

Of the expert group, 2 out of the 6 participants experienced symptoms such as dizziness, loss of balance, and disorientation, while one participant showed symptoms of nausea, eye fatigue, and blurred vision. The participants who experienced vertigo commented on the very realistic sensation of being at different heights on the bridge while inspecting it and looking down, which created the perception of a falling risk.

## 8. Discussion

The analysis of the impact of Virtual Reality (VR) on communication in construction projects highlights its ability to transform work dynamics, improve collaboration, and optimize decision-making. Experts showed a positive attitude towards the technology, increasing their confidence after experiencing it in practical situations. The evaluation indicated that VR is effective in mitigating communication barriers and resolving Requests for Information (RFIs), especially in contexts that require advanced visualization and immersive collaboration.

The proposed communication workflow, based on VR, proved to be more efficient in complex situations such as Approval, Alternative Design Solution, and Other, achieving averages of 4.5 to 4.7 and unanimous preference from the experts. This workflow improved efficiency compared to the current workflow, whose results were less favorable (2.7 to 2.8). In these cases, the implementation of the proposed workflow is considered advisable. On the other hand, for situations like Information Clarification–Conflict Information and Insufficient Information, the current workflow maintained acceptable efficiency levels (3.8), so its optimization is suggested before completely replacing it with the proposed workflow.

The VR experience was also positively evaluated in terms of collaboration, fostering a more effective and enriched work environment. However, challenges related to adapting to the technology and ease of use were identified, which could be improved through future research and design adjustments. Additionally, the need to consider potential symptoms associated with VR use, such as dizziness or vertigo, especially in individuals with pre-existing medical conditions, was observed, recommending caution and controlled usage sessions.

Overall, the results support the implementation of VR in construction projects, emphasizing its ability to overcome communication barriers (CB), optimize RFI resolution, and foster more efficient collaboration. However, its adoption should be tailored to the specific needs of each situation, considering both its benefits and the challenges associated.

*Limitations of the Work*

In the context of this research, the following key limitations are identified:

- **Limited Sample and Testing Scope:** The study was conducted with a small group of experts (6 participants), which limits the generalizability of the results. Due to this sample size, it was not feasible to apply statistical significance tests with an adequate level of reliability; for this purpose, a minimum of approximately 33 participants would be required. In addition, the virtual reality experience was only validated for bridge infrastructure projects.
- **Technical and Functional Constraints:** Although the multi-user environment is designed to support up to 20 participants, it was only tested with a maximum of 4 users (non-VR), and synchronization issues were observed—only the session creator's object movements were visible to others.
- **Scope Restrictions on Communication and RFI Types:** The study did not cover RFIs related to incorrect or questionable information, nor did it address communication barriers such as listening issues or cultural interference. Additionally, some participants reported symptoms of simulator sickness during VR engagement.

## 9. Conclusions

The study focused on a truss railway bridge, analyzing how Virtual Reality (VR) can improve communication between the engineering office and the construction site through a modified workflow for resolving Requests for Information (RFIs). This workflow replaces emails with immersive virtual meetings, using technologies such as HTC Vive headsets and the BIMTable, optimizing collaboration and reducing iterations. Eight VR practices were proposed to mitigate communication barriers, such as lack of trust, unclear objectives, and limited resources. VR enables multi-user experiences with high authenticity, facilitating realistic inspections, element manipulation at scale, and advanced visualization, even in hard-to-access areas.

In the evaluation, RFIs classified as Approval, Alternative Design Solution, and Other showed a significant improvement with the proposed workflow, with an efficiency average 59% higher than the current workflow and ratings of 4.4 out of 5. In contrast, for RFIs related to Information Clarification due to Insufficiency or Conflict, the current workflow maintained an acceptable efficiency, with optimization recommended before a complete switch. Experts highlighted the effectiveness of VR in mitigating barriers, improving decision-making, and fostering more immersive collaboration, although they noted the need for further technological adaptation and training. Challenges related to symptoms associated with prolonged VR use, such as dizziness or disorientation, were also identified, suggesting precautions and future improvements in device design.

In conclusion, Virtual Reality (VR) has potential to optimize communication and collaboration in construction projects. However, its implementation needs to be refined, the evaluation sample expanded, and identified limitations addressed to maximize its impact on similar projects.

This research identifies several areas for future exploration. First, a comprehensive evaluation of current practices is needed to assess how Lean Construction (LC) and Building Information Modeling (BIM) can help mitigate barriers such as conflicting cultural values, political interference, and lack of skills, while also addressing unassessed factors like poor leadership and generational differences. Additionally, further investigation into bidirectional synchronization of object movements in virtual reality (VR) environments could significantly enhance collaboration. The applicability of the proposed workflow to clarify incorrect or questionable information also warrants validation. Moreover, a deeper evaluation of the symptoms associated with VR use is necessary to better understand its potential impact on user health. Expanding the application of VR to other types of infrastructure beyond bridges, as well as increasing the sample size and diversity of participants, would contribute to more robust and generalizable findings. Finally, conducting a detailed cost–benefit analysis of the proposed workflow—assessing its impact on project cost, execution timelines, and other critical management factors—would provide a more comprehensive understanding of its feasibility and cost-effectiveness. Collectively, these research directions aim to optimize the use of VR for mitigating communication barriers and improving collaborative experiences in construction projects.

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