Cost-Effective augmented reality tool for enhanced building envelope panel handling: installation and validation

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Abstract

As part of a project aimed at upgrading older, non-renovated buildings by retrofitting their envelopes to meet the European climate targets required by 2050, a low-cost Augmented Reality (AR) tool was developed to facilitate the renovation and maintenance process. Considering that the renovation process involves a large number of different panels, which are assembled like a large puzzle in the building using plug-and-play techniques, traceability remains a challenge. To facilitate the assembly of the panels, which contain digital information, and using AR techniques, the panels will be displayed on the real building in their final position.

In this way, AR tools will bridge the gap between digital information and the real-world environment, allowing users to visualise information about the position to be installed in the real place. Additionally, the tool will have the option to display further information (such as safety instructions or installation details) related to each panel, ensuring that workers have all necessary information on-site. Developed as a web-based Single Page Application (SPA) compatible with standard smartphones and tablets via WebXR, the tool eliminates the need for expensive hardware or software installations.

The tool demonstrates the feasibility of using a cost-effective AR solution to provide necessary information to on-site operators, as well as generating real-time Key Performance Indicators (KPIs) and alerts that managers can consult.

Keywords

Façade, Building Envelopes, Modular Construction, Installation, Verification, AR (Augmented reality), WebXR, Building Information Modelling (OpenBIM), SPA (Single page application)

DOI

http://doi.org/10.47982/jfde.2025.333

1 INTRODUCTION

The European decarbonisation strategy ("2050 Long-term Strategy," n.d.) is closely aligned with the objectives of building rehabilitation, highlighting the crucial role that envelopes play in achieving these goals. Furthermore, the strategy underscores the importance of industrialisation and prefabrication as key enablers of this transformation.

According to the European Commission, 85% of EU buildings were constructed before 2000, and 75% of them exhibit poor energy performance ("Energy Performance of Buildings Directive," n.d.). This fact underscores the urgent need for large-scale, efficient renovations to align the building stock with modern energy efficiency standards.

In this context, the use of prefabricated panels in building retrofits is gaining recognition for its ability to shorten construction times and enhance energy performance. Prefabrication offers multiple benefits, including reduced waste, minimised disruption to occupants, improved efficiency, faster installation, higher quality, increased safety, and greater sustainability. Numerous European case studies have demonstrated the success of this approach in retrofitting projects, highlighting best practices and effective implementation strategies (Callegaro & Albatici, 2023; Loebus, Ott, & Winter, 2014; Sousa et al., 2013). However, several persistent challenges hinder its optimal implementation.

To support the successful execution of panel-based retrofitting, it is essential to perform effective information management during the whole installation and subsequent validation process. The renovation must be carried out with reliable and detailed knowledge of the building to be renovated, along with a sound understanding of the desired result.

Prefabricated panels demand precise alignment and sequencing during installation. In retrofit scenarios—where existing structures may be irregular or poorly documented—this complexity increases the risk of misalignment, leading to costly rework and delays. While Xiao and Bhola (2021) do not focus specifically on retrofitting, they emphasise that the lack of standardised design processes and real-time feedback mechanisms in prefabricated systems often results in inefficiencies and coordination breakdowns.

Since prefabricated components can be manufactured off-site, it is essential to ensure accurate building measurements and precise data exchange between the design, manufacturing, and construction teams. This coordination requires a high degree of accuracy and attention to detail, particularly during the on-site assembly process, to guarantee a seamless fit and ensure that the prefabricated modules meet the required specifications. Li et al. (2023) also state: "We can only significantly improve the construction process and reduce loss and waste if information is shared throughout the design, manufacture, transportation, assembly, construction, and maintenance phases" (p. 3).

The use of Building Information Modelling (BIM) technology has rapidly expanded among AECO (Architecture, Engineering, Construction, and Operations) professionals. However, it remains primarily focused on new designs and faces several challenges, including high equipment and software costs (Azhar, 2024). BIM is used in façade renovation to ensure accurate data flow as it creates a centralised, accurate, and continuously updated model that all stakeholders can access and rely on. In complex renovation projects, information often comes from multiple sources, such as architectural surveys, engineering analyses, and construction site reports. Without a structured system, this data can easily become fragmented, outdated, or inconsistent. BIM provides a solution by integrating all information into a single environment where changes are automatically updated across the model. This ensures that architects, engineers, contractors, and project managers are always working with the latest and most accurate data. As a result, decisions can be made confidently, errors are reduced, and coordination between disciplines becomes smoother. Ultimately, using BIM to manage data flow prevents misunderstandings, rework, and delays, thereby making the renovation process more reliable and efficient.

The versatility of BIM extends beyond renovation projects, offering significant advantages in other construction domains such as modular construction. In this context, Pan and Zhang (2023) argue that integrating BIM with AI and real-time data analytics is crucial for managing the complexity of modular construction. They highlight that event log mining and real-time alerts enable proactive decision-making, which is otherwise hindered by the reactive nature of traditional monitoring systems. "Without real-time data and alerts, managers are unable to make timely decisions, which can lead to inefficiencies, delays, and increased risk" (Pan & Zhang, 2023, p. 1092).

In prefabricated construction, workers often face challenges interpreting digital models or understanding complex installation sequences, especially when they lack prior experience with BIM or AR technologies. According to Azhar (2011), Building Information Modeling (BIM) significantly enhances understanding by allowing users to visualise construction processes in a simulated environment. This not only reduces the need for extensive training but also helps bridge the skill gap between experienced professionals and newer workers, making it easier for them to perform complex tasks accurately and confidently."BIM enables visualisation of construction processes, which enhances understanding and reduces the need for extensive training" (Azhar, 2011, p. 245).

Li and Wu (2021) argue that traditional safety and management systems are insufficient for prefabricated construction due to the shift from on-site casting to off-site manufacturing and on-site hoisting. They emphasise that real-time monitoring of transportation, stacking, and installation is essential to prevent safety incidents and ensure workflow efficiency. The authors propose a BIM-RFID-based system to provide real-time updates and alerts, enabling managers to respond proactively to issues as they arise.

The integration of BIM with complementary technologies is transforming how information is managed and delivered across the construction lifecycle. While BIM ensures centralised and accurate data flow, its full potential is realised when combined with tools like RFID, augmented reality (AR), and artificial intelligence (AI). These integrations address the critical challenge of making complex digital information accessible and actionable on-site.

However, despite these advancements, a significant hurdle remains: effectively delivering BIM-based information to the workplace in a format that is both simple and intuitive. To truly empower on-site personnel, there is a pressing need for systems that can translate detailed digital models into clear, actionable guidance, conveying installation procedures, safety instructions, technical specifications, and final positioning of prefabricated modules in a user-friendly manner.

In this context, the main contribution of the research lies in the creation of a low-cost AR tool for use in the construction field, which guarantees both the reliability of the data presented to the operator and the integration of data generated during its use. To achieve this, the tool overlays digital elements onto the real-world view, providing users with contextual, real-time information about the construction site. This reduces reliance on plans and photographs and enables operators to work more efficiently and safely. BIM model integration is a mandatory requirement to maintain data consistency and comply with various EU standards, such as the EU Directive 2014/24/EU (European Parliament and Council, 2014). The choice of a low-cost device as the platform for demonstrating the tool stems from the goal of making it as affordable as possible, encouraging widespread market adoption.

The objective of this research is to develop a low-cost AR tool to assist in the installation and verification of building envelope panels. Despite its low cost, the tool includes a full suite of augmented reality (AR) capabilities. These include real-time 3D model overlay onto the physical environment, spatial anchoring, interactive data display, and dynamic alignment aids to ensure accurate panel positioning. This tool should deliver detailed information about the panels (safety guidelines, instructions) and display the final placement of the panels on the actual building using AR. The tool will offer three primary features:

- AR-guided installation support: The tool enables operators to visualise the exact final position of each panel directly on the building through augmented reality. By overlaying digital panel models onto the physical structure in real time, the system helps installers align and place components accurately. This reduces reliance on printed plans or manual measurements and minimises the risk of installation errors.
- Real-time data capture and alert generation: During installation, the tool captures status updates and generates alerts based on operator input (e.g., panel accepted or rejected). This information is instantly synchronised with the central system, ensuring that managers receive up-to-date insights from the field.
- KPI monitoring and progress tracking: Managers can access a dashboard that displays key performance indicators such as the number of panels installed, verified, or rejected, along with real-time alerts. This supports informed decision-making and project oversight.

The primary advantage of the tool is its remarkable accessibility, enabling users to operate it without investing in expensive hardware or relying on proprietary data formats. The tool is designed to function on consumer-grade devices such as smartphones or tablets, making the technology widely usable without specialised AR headsets. This accessibility promotes broader adoption and supports more inclusive digitalisation across the construction sector, contributing to efficiency, safety, and sustainability goals. This ensures that even small and medium-sized enterprises can benefit from advanced digital construction technologies without incurring prohibitive costs.

2 STATE OF THE ART AND INNOVATION

AR is increasingly transforming the construction industry by enabling the overlay of digital models onto physical environments. This capability not only enhances real-time visualisation but also facilitates more efficient decision-making on the job site. As Nassereddine et al. said:

> "Respondents were asked to elaborate on their experience and use of the technology and they frequently reported that AR improves project visualisation by allowing owners and contractors to virtually walk through the project, supports decision making on-site by bridging the gap between office and field...". (Nassereddine et al., 2022, p. 11)

In order to make use of the AR, a physical device with the necessary capabilities is required. These devices are currently divided into two types: Head-Mounted Displays (HMDs) and mobile devices. Both vary in cost and performance. HMDs are more expensive due to their specialised technology, including advanced displays, sensors, and processing power. Mobile devices, on the other hand, are more affordable, offering sufficient performance for basic AR tasks, with high-end models providing enhanced features for smoother, more accurate experiences.

HMDs offer a more immersive experience and even allow users to remain hands-free; however, their shorter battery life and ergonomic issues (which may even prevent the use of Personal Protective Equipment (PPE)) make them difficult to use in construction environments. In addition, due to their cost and limited compatibility, their adoption is not widespread, reflecting the current reluctance among construction companies to utilise them (Bressan, Scarpa, & Peron, 2024).

Continuing the focus on HMDs, Dallasega, Schulze, and Revolti (2022) analyse whether AR can overcome the barriers to implementing visual management (VM) in mechanical, electrical, and plumbing (MEP) construction project markup work. As a case study, they performed a MEP installation in a multi-story apartment building, utilising an augmented reality helmet (HMD) to support the marking work. The results showed that the AR can save time and leads to satisfactory levels of accuracy, as well as reducing training effort and resistance to the implementation of VM. The hardware used consists of a high-cost HMD device for use in AR in the construction field. Rankohi et al. (2023) go even further, offering in their book *Applications of Augmented Reality - Current State of the Art*, a review of AR technologies and their applications in architectural, engineering, and construction (AEC) projects. It discusses the challenges of applying AR in these types of projects and includes a case study on the application of AR in a manufacturing plant in Canada. It demonstrates the use of QR markers to make the link between the real world and the virtual world. The device chosen for this case study is HoloLens 2, a niche market device with a high price tag.

The integration of AR in modular construction has been explored through the use of high-cost HMDs (Pan, Chen, Fu, & Lu, 2023). The study discusses the use of a centralised database and multiple profiles for different visualisations. In this setup, the HoloLens, a head-mounted display, is used to bring AR into the construction environment.

In Europe, BIM is increasingly regulated and standardised through several key frameworks. The EU Directive 2014/24/EU (European Parliament and Council, 2014) encourages the use of BIM for publicly funded construction projects across member states. The ISO 19650 standard (International Organization for Standardization, 2018), widely adopted throughout Europe, defines the processes for organising and digitising information about buildings and infrastructure using BIM. Additionally, the EN 17412-1:2020 standard (European Committee for Standardization, 2020) focuses on defining the Level of Information Need in BIM, helping to structure what information is required at different stages of a project. Many European countries, such as the UK, Germany, France, and Italy, have introduced national mandates or roadmaps that align with these broader EU standards and ISO guidelines. Supporting these efforts, the EU BIM Task Group (EU BIM Task Group, 2017) brings together public sector bodies across Europe to share best practices and promote a unified approach to BIM adoption. These collective efforts demonstrate a clear commitment across Europe to harmonise BIM practices, ensuring greater efficiency, interoperability, and innovation within the construction industry.

The integration of AR and BIM is a topic of growing interest and has been the subject of considerable research and practical exploration. Gerger, Urban, and Schranz (2023, p. 3) examine the potential uses of AR in building authority processes, using the city of Vienna as a case study. The article concludes that AR, especially when combined with openBIM, has significant potential to accelerate building authority processes and improve citizen participation, as it cites ''Applications for mAR are often geared towards the design and preconstruction phases, as no exact location or superimposition is necessary.''.

Similarly, Pan and Isnaeni (2024) explore the integration of AR and BIM to improve construction inspection. The authors propose a model that combines these technologies to improve data life cycle management and the efficiency of construction management practices. The AR component was developed using Unity 3D and Gamma SDK, resulting in an .apk file for Android devices. To integrate the BIM file into the app, a conversion is required, meaning the original BIM file is not directly used in the application.

As in the previous case, Chai et al. (2019) study the integration of BIM with AR to improve the applicability of BIM in fieldwork within the construction industry. The authors examine the credibility of the AR-BIM pairing using a case study that replicates the system by combining Unity 3D and C# and a conversion of the BIM file. The results indicate that, although the developed system is still evolving, integrating AR with BIM is feasible, thereby maintaining the benefits of both BIM files and AR.

As shown in the examples above, the integration of AR with BIM is predominantly accomplished through the use of expensive head-mounted display (HMD) devices, the conversion of BIM to other file formats, the deployment of applications that require prior installation on the target device, or a combination of the aforementioned technologies. These approaches, while effective, often present limitations in terms of accessibility, cost-efficiency, and ease of use. Mobile devices, which are capable of delivering AR experiences at a substantially lower cost, offer a viable alternative. Equipped with AR capabilities, these devices provide proven portability, autonomy, and economic efficiency. Moreover, given their widespread use, mobile devices represent a more practical and cost-effective solution, particularly for small and medium-sized enterprises with limited budgets.

In conclusion, the implementation of a low-cost AR tool for the installation and verification of panels in building envelopes represents a practical and accessible solution that enhances efficiency and safety in construction processes. Integrating the BIM asset directly into the application without conversion ensures that we both adhere to and leverage the benefits of various European directives and standards. To take advantage of mobile devices and web technologies, a cross-platform experience can be achieved without the need for native applications, thus eliminating compatibility issues and outdated versions.

3 METHODOLOGY

The development of the tool follows an iterative, user-centred methodology focused on enhancing construction workflows through role-specific functionality and AR integration. Designed for both managers and operators/installers, the tool supports dual operating modes: a non-AR interface for managers to monitor real-time progress and KPIs, and an AR-enabled interface for installers to visualise, install, and verify façade panels on-site.

Installation and validation processes are structured around guided AR workflows. Using a physical reference point, installers align the virtual model with the real building, then scan and assess each panel. The system displays relevant information, such as location, specifications, and safety data, via semi-transparent overlays, allowing continuous situational awareness. Decisions made during installation or verification automatically update the system, generating alerts and adjusting KPIs accordingly. A colour-coded validation system (blue, green, red) helps quickly identify panel status.

Initial testing is conducted using the OpenBIM model of an experimental building, a full-scale facility ideal for iterative development and validation. This controlled environment enables early detection of issues and enables real-time refinement. Following successful testing, the tool will be deployed in real renovation scenarios, validating its performance in diverse European contexts and ensuring practical scalability and operational reliability.

3.1 TOOL WORKING MODES

The tool developed will have dual use, depending on the end user, as shown in Figure 1.

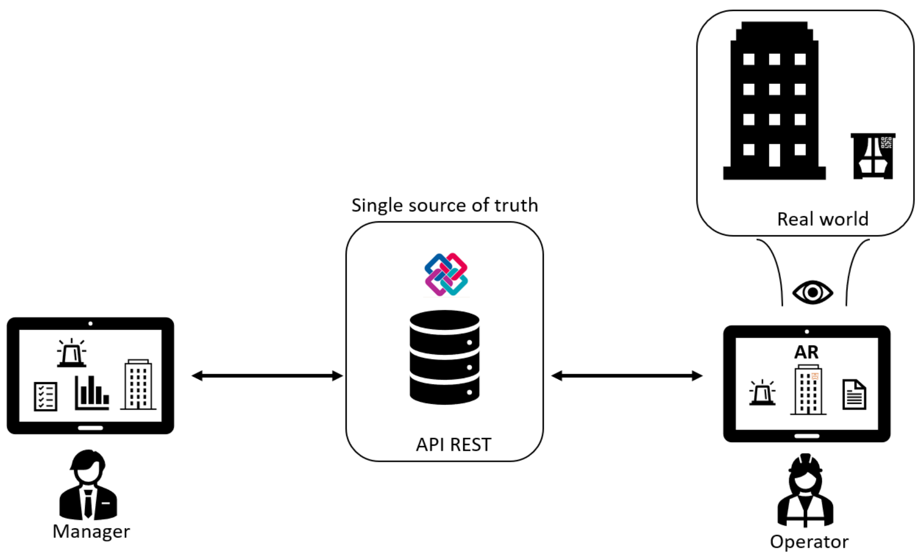

FIG. 1 *Usage possibilities.*

- Manager: No AR capabilities. The interface designed for the manager profile does not incorporate augmented reality functionalities. However, it enables real-time monitoring of the status of individual panels, categorised as idle, installed, invalid, or quality-checked, with dynamic updates as the installation progresses. Additionally, the manager has access to system-generated alerts. This component of the tool is intended to facilitate the tracking of construction progress and overall project status through the use of key performance indicators (KPIs).
- Operator/installer: With AR capabilities. This part of the application will allow the overlay of the virtual building over the real one, enabling the scanning of different panels and displaying their final location as well as information related to their installation and/or security details. When performing both the installation and the verification of the installed panels, the information will flow in real time, generating changes in the manager's part, updating the different KPIs (total number and percentage of the status of the panels, as well as the number of alerts generated).

This dual-purpose approach enhances overall productivity and accuracy within construction workflows.

The tool itself will detect if the device has AR capabilities, and if it does not, it will not allow the operator/installer mode, thus preventing improper operation.

3.2 LINK BETWEEN AR AND REAL WORLD

When using the tool in installer mode and using the AR capabilities, the virtual building is overlaid over the real one. To achieve this, it is necessary to establish a reference and pivot point in the physical environment, which will serve as the basis for accurately aligning the virtual building with the real-world context, as illustrated in Figure 2.

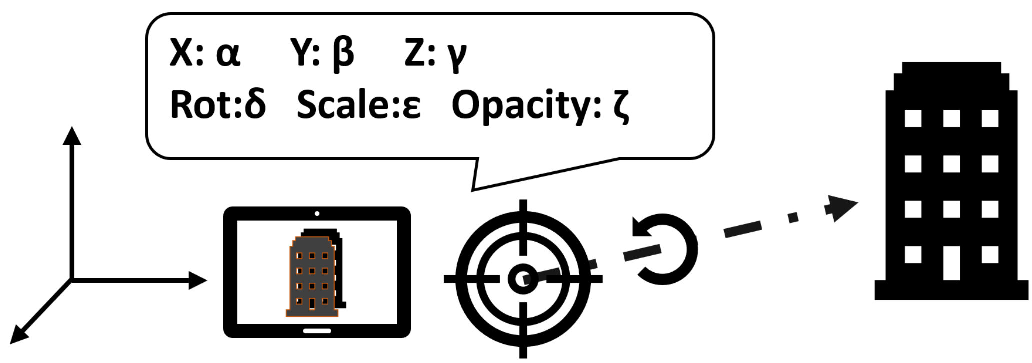

FIG. 2 *Reference and pivot point.*

By identifying the reference point in the physical environment through AR mode, the tool will precisely position the virtual building in its final location. It will use the necessary data from the BIM model, along with the relative positioning information stored within the tool, to ensure accurate placement.

The functionality of being able to move, scale, rotate, and control the transparency in the virtual building will be added, so that changing the reference point does not pose a problem. The visualisation of the virtual world can be adapted to the conditions of the real world (increased luminosity, rain, fog). Once the final position of the virtual model has been modified with respect to the reference point, it is possible to persist it in the tool.

3.3 PANEL INSTALLATION PROCESS

The tool is designed to assist operators with the repetitive task of installing panels on the building. A workflow has been designed to guide the installer through each step required to install the panels using the tool. These steps include identifying the panel, displaying relevant information (such as specifications, instructions, and safety data), and visualising the final installation location in AR. The workflow is depicted in Figure 3.

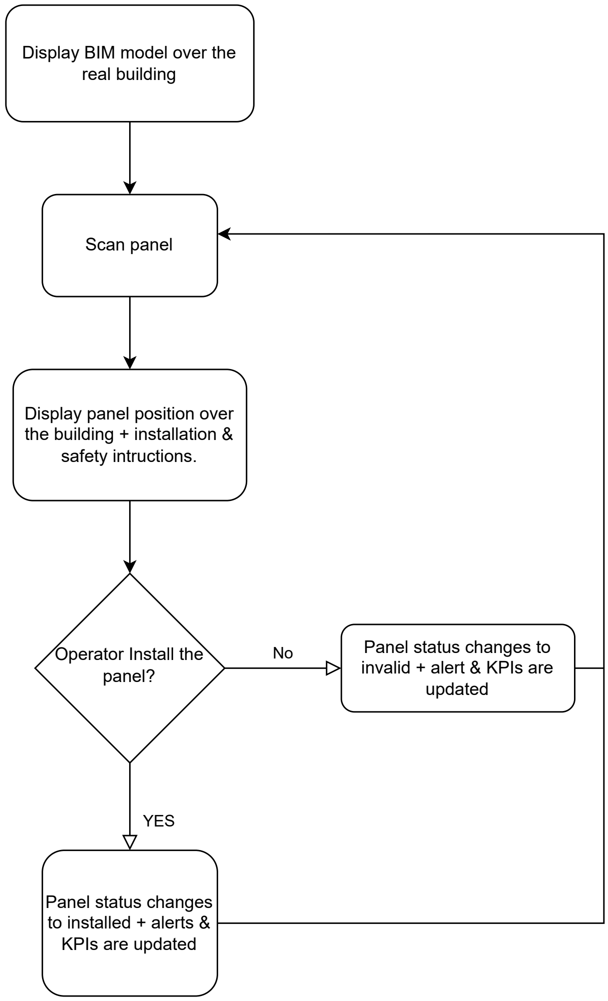

FIG. 3 *Panel installation flow.*

The panel installation process begins as follows: The operator will position the building in its actual location using the reference point, along with the building data, and make any necessary adjustments to fine-tune its alignment to the desired position. Once the virtual building is adjusted, the next steps will be repetitive (the addition of panels), so that there is no need to leave the AR environment.

In the tool, the panel scanning mode will be selected, and the installation of each panel will proceed accordingly. Each panel will be scanned to retrieve the relevant information from the tool, which will then display the panel's final position on the virtual building in AR, along with any associated usage instructions and safety considerations.

The way to display the information in AR will be through a semi-transparent menu, allowing the environment to remain visible at all times. The panel will be highlighted in the building using the black colour, so that focusing with the device towards the building highlights its position.

The operator/installer with the available information will decide whether to install the panel or to reject it (due to panel failure). Both when rejecting the panel and when validating it, the information in the tool will be updated, generating the necessary alerts and automatically updating the KPIs.

3.4 PANEL VALIDATION PROCESS

Once the panel installation is complete, it is possible to verify the panels to ensure that the final positions match the specifications. For this, the workflow will be slightly different from the installation process, as shown in Figure 4.

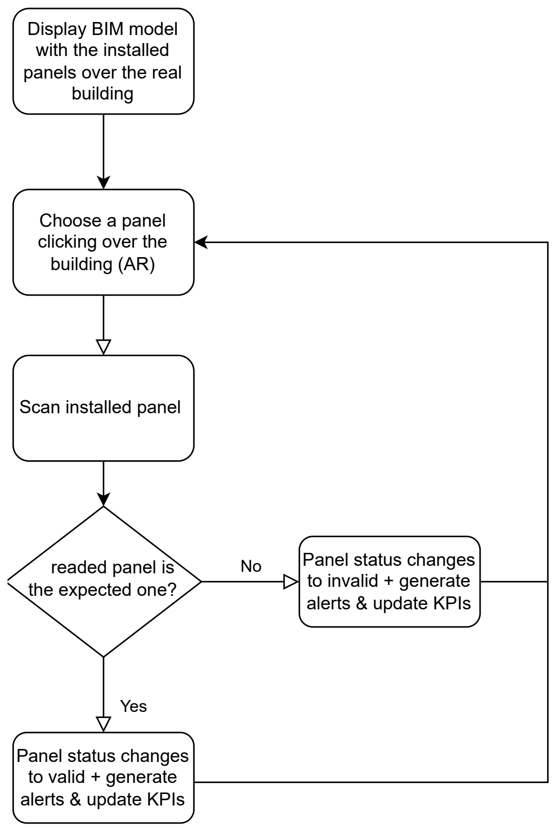

FIG. 4 *Panel installation flow.*

The first step is to load and position the building by reading the reference point and making precise adjustments (position, rotation, scaling, and opacity) if necessary. In the tool, select the verification mode, which will reveal with a colour code the different states of each of the panels:

- Blue colour: Panel installed but not verified.
- Green colour: Panel installed and verified.
- Red colour: Panel installed in the wrong position.

To initiate the verification process, a panel will be selected from the AR building by clicking on it. Once the panel is selected, it will be scanned, and the tool will automatically verify that the selected panel is the correct one. In this process, the information on the tool will be automatically updated, allowing alarms (if any) to be generated and corresponding KPIs to be updated.

In the same way as during the installation process, once a panel has been verified, regardless of the result, the rest of the panels can be verified, as this is done in the same AR session, thus speeding up the whole workflow.

3.5 TOOL MANAGER MODE

The manager mode enables real-time monitoring of construction progress without the use of augmented reality. To support this functionality, a dedicated interface has been developed, allowing users to track the status of individual panels as well as access key performance indicators (KPIs) relevant to project supervision.

In this initial version of the application, KPIs have been implemented to represent the distribution and relative proportions of panels across their installation statuses (idle, installed, invalid, or quality-checked). Additionally, the interface includes a section for visualising system alerts, providing further insight into the ongoing installation process.

Real-time updates will be received, and the interface will display a notification, alerting the manager to the changes that have been made.

3.6 CONTEXT AND EXPERIMENTAL FRAMEWORK

The AEGIR (AEGIR EU Project, 2024) project is a consortium of 30 partners from nine EU countries that focuses on the development of modular, renewable, and industrialised building envelope solutions for low-energy renovation. AEGIR designs scalable and customisable renovation envelope systems tailored to diverse building types, climate zones, social contexts, and occupant needs across Europe.

Figure 5 illustrates the diversity and range of panels that may be involved in an envelope renovation.

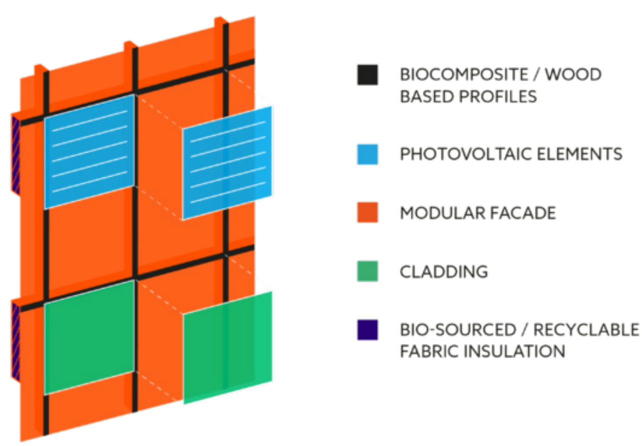

FIG. 5 *Different envelope panels. (AEGIR - EU Project, 2024)*

To carry out the development and testing process, the OpenBIM (IFC) file of the experimental building KUBIK was used, which is located in the Parque Científico y Tecnológico de Bizkaia in Derio, Bizkaia province, Basque Country, Spain (Tecnalia, n.d.). This is an experimental facility created to develop and validate new concepts, products, and services in full-scale tests. The infrastructure comprises a building capable of reconfiguring up to 550 m^2, spread across a basement and three above-ground floors. The building is fully demountable and allows for the reconfiguration of simultaneous scenarios at the construction level by replacing façade, roof, and partition components.

By maintaining a test and development environment that closely mirrors the final use case, the application's various functionalities have been rigorously tested immediately upon implementation. This approach has enabled rapid identification and resolution of issues, ensuring that each feature performs reliably under realistic conditions. It also facilitates iterative development, where feedback from early testing can be quickly incorporated into subsequent updates. Furthermore, the final deployment sites of the AEGIR project will integrate this AR-based technology, transitioning its validation from controlled laboratory settings to real-world renovation scenarios across Europe. This broader deployment not only serves to confirm the robustness and adaptability of the system in diverse environments but also provides valuable insights into its practical utility and user experience in actual field conditions. By bridging the gap between development and deployment, the project ensures that the technology is both technically sound and operationally effective in supporting large-scale energy renovation efforts.

4 RESULTS

4.1 SPECIFICATIONS AND FUNCTIONAL REQUISITES

A Single Page Application (SPA) is a web application that loads a single HTML page and dynamically updates its content as the user interacts with the app, providing a smoother and faster experience without requiring the entire page to reload. The solution will be approached using a SPA-type tool, both because the existing technology allows us to fulfil all the functional requirements described below and because of the advantages of a multi-platform solution without the need for installation, which this research aims to achieve.

- AR capability in a web environment. This capability will be fundamental to carrying out the development of the solution. This will eliminate the need for proprietary hardware, and the solution will be compatible with a wide range of devices.
- Ability to display openBIM elements in an AR environment. It is essential to display both the building and the construction elements in the real environment.
- Ability to store information and distribute updates in real time. For the application to have a significant impact on the operators, a real-time information flow is critical, ensuring that alarms and updates are instantaneous and the information displayed by the application is the latest available.
- Ability to view the overall status of components and different KPIs of the building's condition. The SPA shall be able to operate in an AR environment or in normal web mode, depending on the user's needs, so that the information provided depends on the end user.
- Ability to capture real-world information efficiently. While it is possible to have the operator enter the unique identifier of each panel manually, we can eliminate this step to make the solution dynamic by using image capture, making the whole application flow more comfortable and faster.
- Ability to organise and display information effectively across multiple screen sizes, ensuring a seamless and responsive user experience on devices ranging from smartphones to larger desktop monitors.

4.2 DEVELOPING TOOLS AND TECHNOLOGIES

React is chosen for the development of SPA. React is a JavaScript library used to build user interfaces, particularly those that require efficient and dynamic updates. React allows developers to create reusable components that handle their own state, making it easy to build complex web applications in an organised and maintainable manner.

The creation of the SPA has been carried out considering the principles of responsive design, so it is prepared for a wide range of devices, from PCs to mobile devices. Depending on the device being accessed, the information on the screen will be optimally organised to make the best use of the screen's resources. Figures 6 and 7 show the variability of screen sizes and the corresponding rearrangement of content.

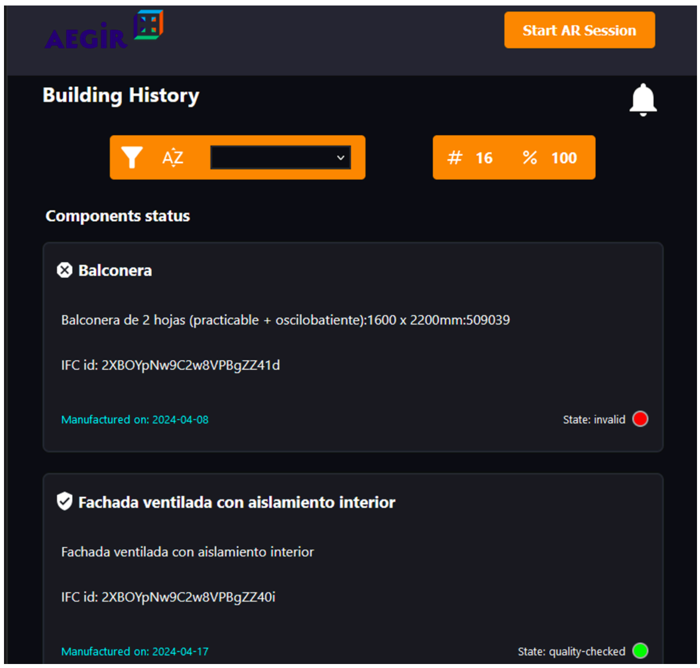

FIG. 6 *SPA on iPad Pro screen.*

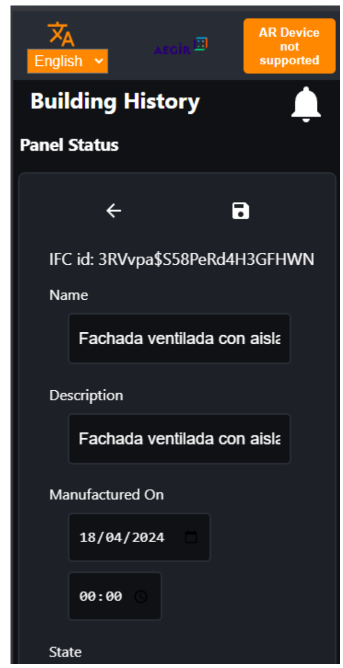

FIG. 7 *Edit panel on Samsung Galaxy S8+ screen.*

Another point to consider when creating the menus is the need to make them usable with a single finger or pointer, so that the operator does not have to type at any time. Thus, all the necessary commands have been translated into elements that can be operated with a single finger (buttons or sliders).

For the 3D viewing capabilities of OpenBIM (IFC) files and the use of AR, the Three.js library has been used ("Three.js – JavaScript 3D Library," n.d.). Three.js is a powerful JavaScript library that simplifies the creation and display of 3D graphics in the browser, leveraging WebGL for rendering. Three.js can be used with IFC files by using libraries designed to interpret BIM data. This compatibility allows the visualisation and rendering of IFC data in 3D directly within web applications. The same library allows the user to colourise, rotate, increase, or hide each of the elements of the 3D environment, so that the information can be displayed as another visual element.

WebXR ("WebXR Device API," 2024) is a technology for obtaining AR in web-based applications due to its cross-platform compatibility, cost-effectiveness, ease of deployment, and real-time interaction capabilities. It builds upon earlier standards, such as WebVR, and extends capabilities to include AR, enabling developers to create applications without the need for specialised hardware or software installations. It enables AR experiences to function across a wide range of devices, including smartphones, tablets, and AR glasses, all through standard web browsers like Chrome, Firefox, and Edge. The technology also supports real-time updates, allowing users to interact with 3D models and digital content as they move or change their perspective, further enhancing user engagement. Furthermore, WebXR integrates seamlessly with existing web development tools and frameworks, such as HTML, JavaScript, and WebGL. Overall, WebXR provides a scalable, accessible, and efficient solution for integrating AR into web applications. In addition, by not requiring a native application, version fragmentation is avoided, as all devices will have access to the latest version hosted on the server. Figure 8 shows the wide range of web browsers that support this capability.

Feature Name	Standardisation	Chrome	Safari on visionOS	WebXR Viewer	Magic Leap Helio	Samsung Internet	Meta Quest Browser	Microsoft Edge
WebXR Core	Explainer Spec MDN	Chrome 79	Behind a feature flag	iOS	Magic Leap Helio 0.98	Samsung Internet 12.0	7.0, December 2019	Edge 87 on Windows Desktop Edge 91 on Hololens 2
WebXR AR Module	Explainer Spec MDN	Chrome for Android, 81		iOS	Magic Leap Helio 0.98	Samsung Internet 12.1	24.0, October 2022	Edge 91. Hololens 2 only
WebXR Gamepads Module	Explainer Spec MDN	Chrome 79			Partially supported on Magic Leap Helio 0.98	Samsung Internet 12.0	7.1, December 2019	Edge 87 on Windows Desktop Edge 91 on Hololens 2
Hit Test	Explainer Spec MDN	Chrome for Android, 81		iOS		Samsung Internet 12.1	25.3, January 2023	Edge 93. Hololens 2 only
DOM Overlays	Explainer Spec MDN	Chrome for Android (Mobile), 83		iOS		Samsung Internet 14.2		

FIG. 8 *Detail of support table for the WebXR Device API ("Immersive Web Developer Home," n.d.)*

Access to and storage of the information is carried out using the STRAPI tool, an open-source content management system (CMS) that allows developers to build, manage, and distribute content efficiently ("Strapi - Open Source Node.js Headless CMS," n.d.). STRAPI features WebSocket technology that enables real-time, two-way communication between client and server. This is essential for applications that require real-time updates, instant notifications, or real-time collaboration. In this way, information can be stored and notifications managed in real time with a single CMS.

For real-world, information-capturing purposes, the chosen option will be the use of QR (Quick Response) codes. The ease of creating them (there are a multitude of libraries and even web pages) and the amount of information they can store make them an ideal candidate. QR codes offer numerous benefits for image capture in a construction environment, streamlining management and providing swift and efficient access to information. QR codes can be easily scanned with mobile devices, streamlining the real-time updating and exchange of data, thereby optimising communication between the various agents involved in construction. This technology also contributes to reducing errors and increasing productivity, as it provides instant access to the necessary information, thereby avoiding wasted time and potential errors that can occur when the user manually enters the information.

Development has been completed using the TypeScript programming language ("JavaScript With Syntax for Types," n.d.). This is an open-source programming language based on JavaScript, which adds optional static typing and other advanced features. Both Three.js and STRAPI support integration with TypeScript, so we will use a single programming language throughout the solution.

The Visual Studio Code IDE has been used as a development environment, and Vite has been used as a compilation tool ("Vite," n.d.). Vite stands out for its flexibility and modularity, allowing developers to choose the tools and technologies that best suit their projects without being limited by rigid configurations.

4.3 DATA ACCESS

The consumption of the information by the SPA will be done through the STRAPI CMS. For this, we will use two different accesses:

- REST API to obtain the details of the elements, such as the installation details of the panels or the geometry of the building.
- WebSocket for obtaining database changes in real-time, such as creating alerts or modifying the status of any panel. Thus, as soon as a change in the database needs to be displayed in the SPA, the necessary actions will be triggered to bring this information to the device.

After evaluating several options, MySQL was selected as the database solution. The general schema of the database is shown in Figure 9, which outlines the structure and relationships between the data elements.

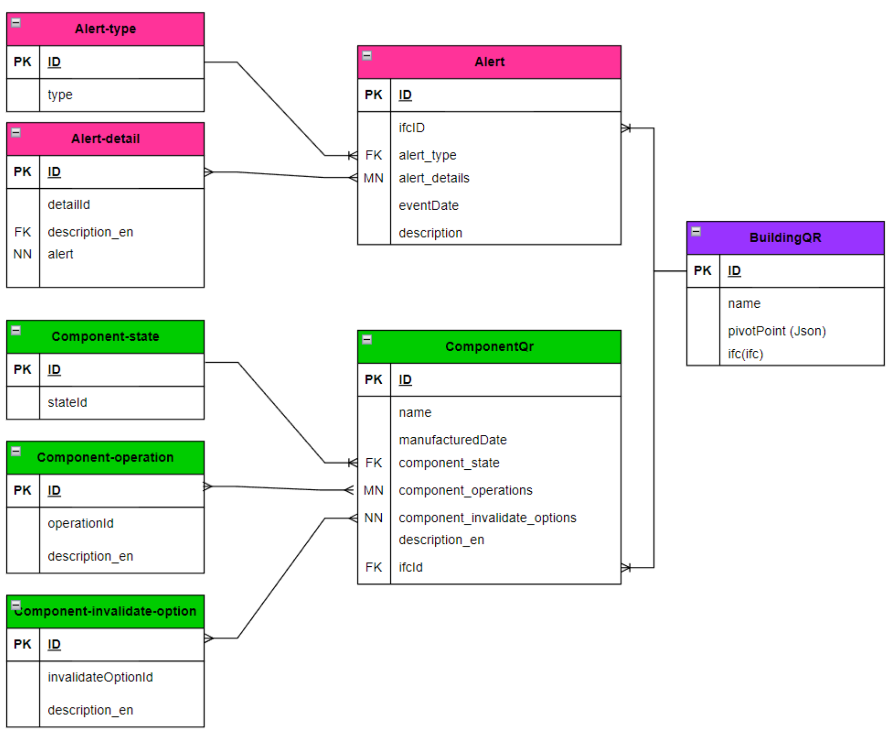

FIG. 9 *Database schema*

As shown in the schema, each panel is identified by its unique ID from the OpenBIM (IFC) file, allowing the tool to link panel-specific information — such as installation details, safety data, and current status (installed, verified) — directly with the corresponding BIM data.

To enhance the user's ability to access information while using the AR component, automatic QR code scanning will be employed. These QR codes will serve two primary functions: first, to define the reference point and retrieve the corresponding BIM file, and second, to capture the panel ID, enabling the retrieval of all relevant information required for the installation or verification process.

The automatic reading of QR codes will significantly reduce the risk of human errors during panel identification, ensuring that each panel is accurately matched with its corresponding data. This streamlined process not only enhances accuracy but also minimises the time spent on manual checks or corrections. By eliminating the possibility of misidentification or oversight, the overall workflow becomes more efficient, leading to faster and more reliable panel installations or verifications. Figure 10 shows an example of 2 QR codes.

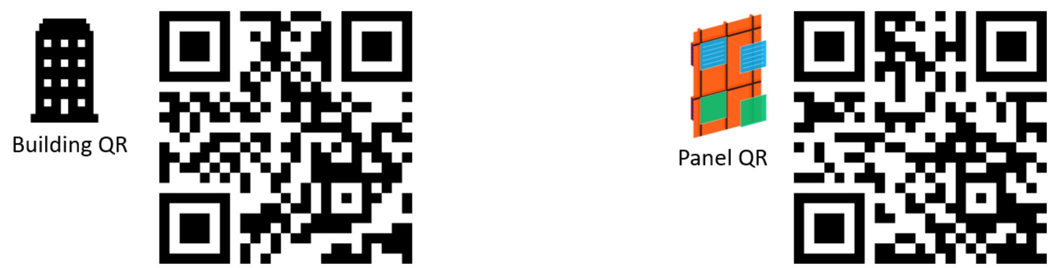

FIG. 10 *QR types.*

4.4 MANAGER MODE

This part of the SPA is the one that the construction manager will use, as it contains the global information about the construction status, and also allows modification of the data that operators/ installers can receive.

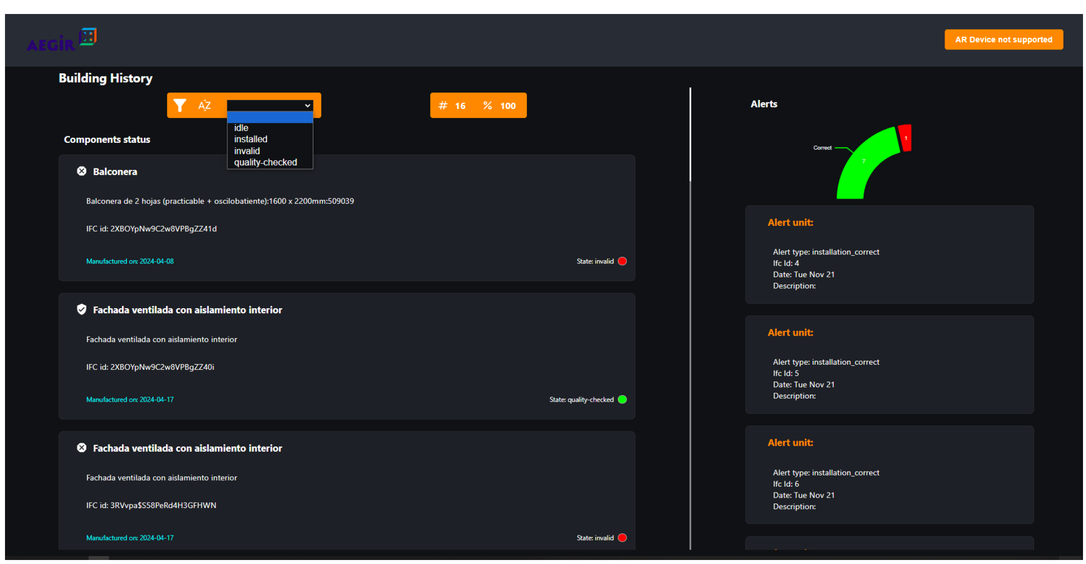

FIG. 11 *SPA in PC(Firefox).*

The interface includes several key features designed to enhance usability and provide comprehensive project monitoring:

- Button to Start AR (Figure 11, top right corner): This button allows users to initiate the AR session, provided the device supports AR capabilities. Activating this feature enables access to operator or installer mode for on-site interaction with the virtual building. The application automatically detects whether the device has AR capabilities, and access to these features will only be available if the device is compatible.
- Building History (Figure 11, centre left section): This section displays detailed information for all panels, including their current status and specific details. The list is fully editable, allowing authorised users to update the status or modify the information of each panel as necessary. Users can filter panels by status and view key performance indicators (KPIs), such as the completion percentage and the total number of panels.
- Alerts (Figure 11, centre right section): This section presents alerts along with detailed information about each issue. It also includes a graphical representation of the various types of alarms received, enabling quick identification of critical problems.

The information presented within the application is continuously synchronised in real time through its connection to the database via WebSocket. This ensures that users always have access to the most recent data regarding panel statuses, alerts, and project progress. Furthermore, each time an item or alert is updated in the system, the application automatically generates a notification, displayed prominently in the upper right corner of the interface. This feature enhances user awareness and responsiveness, ensuring that operators and managers are promptly informed of any changes or critical updates requiring their attention.

In this version of the application, KPIs have been implemented to display both the total number and the relative percentage of panels in each installation status, namely, idle, installed, invalid, or quality-checked. For instance, it may indicate that 60 out of 120 panels have been installed, representing 50%. These metrics provide a clear and immediate overview of the installation progress, enabling stakeholders to monitor performance and identify potential bottlenecks in real time. Furthermore, the application also presents the total number of alerts generated throughout the process, distinguishing between correct and incorrect alerts. This distinction is crucial for assessing the reliability of the alert system and for identifying areas where improvements in detection accuracy may be needed. By consolidating these insights into a single interface, the application enhances operational transparency and supports data-driven decision-making.

Additionally, the KPI dashboard is designed with flexibility in mind, allowing it to be tailored to fulfil the specific needs of different users or teams. Whether it's adjusting the metrics displayed, modifying thresholds, or integrating additional data sources, the system can be customised to align with varying operational goals and user preferences.

4.5 BIM OVERLAY IN AR

If the device is equipped with AR capabilities, the system will prompt the user for permission to access the device's camera when the AR session begins. This access is essential for scanning QR codes, which serve as reference points for positioning and retrieving relevant panel information. Granting camera access ensures seamless integration between the physical environment and the virtual data displayed in the application.

To effectively use the tool, it is imperative to position the virtual building precisely over the physical structure. This is accomplished by scanning the reference point, a QR marker that contains the relevant information. Once that QR code is successfully scanned, the virtual building will be downloaded and integrated into the AR session.

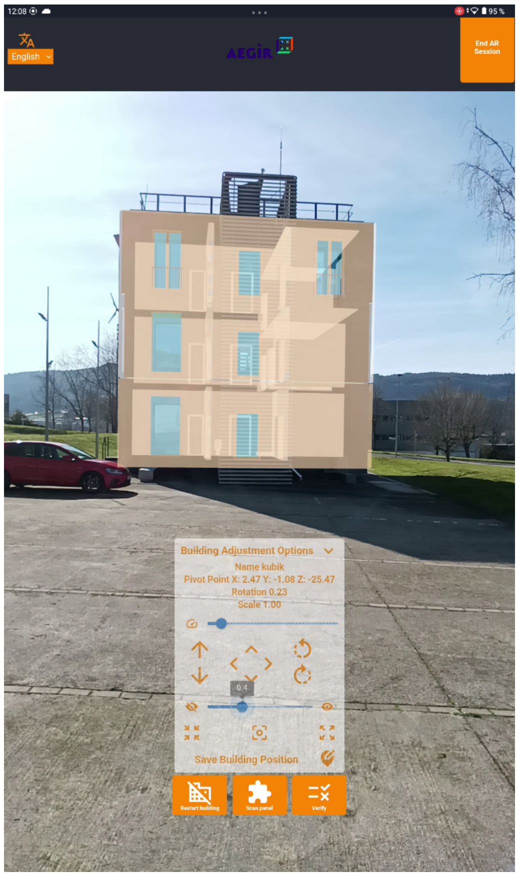

FIG. 12 *Building with edit menu overlay.*

FIG. 13 *Panel placed in the building with the installation details.*

Figure 12 shows the virtual building in its final position together with the superimposed adjustment menu. If needed, its position can be fine-tuned using the menu provided for this purpose.
The decision has been made to make all menus and information available in AR semi-transparent for better integration with the environment.

One of the most helpful functionalities for the integration into the real environment is the control of the virtual building's opacity, allowing the operator or installer to select the appropriate value based on their specific requirements and prevailing environmental conditions.

Once the virtual building has been accurately positioned, the installation or validation of panels can begin by using the options available on the tool's interface.

As the interaction in the application is set up, it is possible to switch between panel installation and panel verification. This facilitates use in changing environments, since it is possible to take advantage of times when installation cannot be performed (e.g., due to adverse weather conditions) to perform validations, or vice versa.

4.6 INSTALLING PANELS

When in panel installation mode, the first action required is to scan the panel's QR code. With the information available in the QR, the tool will access the DDBB and retrieve the panel details. This information will be displayed in AR in two ways, as shown in Figure 13:

- Displaying the panel's position on the building in black: This ensures precise identification of the panel's final placement, eliminating any possibility of error. The operator or installer may freely move around the construction site with the AR session active, allowing them to adjust their viewpoint and obtain a clearer perspective of the panel's location if needed.
- Presenting installation and safety instructions in card format: The relevant information is displayed as overlaid, semi-transparent text, providing clear and accessible guidance without obstructing the user's view of the working environment.

Once we have performed the panel scan, we can proceed with two actions:

- Accept the panel and mark it as installed: This will update the details in the database and the panel will be ready for further verification.
- Reject the panel and mark it as invalid: A list of rejection reasons will be displayed, and after selecting the one that fits the reality, we will be able to reject the panel.

Both actions will update the database, updating the KPIs and generating the corresponding alerts, which will be sent to the manager in real time.

4.7 VALIDATING PANELS

By using the verification mode, the correct placement of the panels will be confirmed, ensuring that each panel is installed in its designated position. All panels subject to verification are displayed on the virtual building, with colour coding to indicate their status: blue for installed, green for verified, and red for rejected, as illustrated in Figure 14.

FIG. 14 *Panel placed in the building with colour codes.*

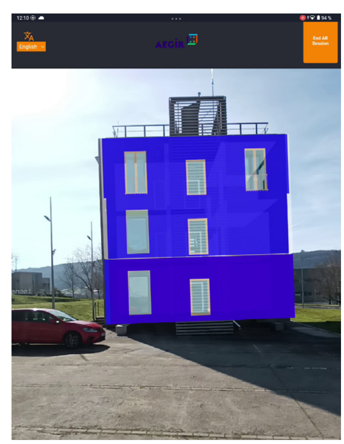

FIG. 15 Panels installed.

The user is required to select a panel and subsequently scan its corresponding QR code to confirm that it matches the information specified in the openBIM file. In Figure 15, all selectable panels are highlighted in blue. This designation indicates that these panels have been installed but have not yet undergone the verification process, meaning they have neither been validated nor rejected. This visual representation helps differentiate the panels that require further inspection or confirmation from those that have already been assessed. Additionally, the interface provides the ability to adjust the opacity of the panels, facilitating clearer visualisation and aiding in the selection process.

After selecting a panel in the verification mode, the user should approach the corresponding physical panel on-site and scan its QR code. Once the tool retrieves the panel information from the database, one of two outcomes will be displayed:

- Valid panel: (Figure 16) The scanned panel matches the designated position and is correctly installed.
- Invalid panel: (Figure 17) The scanned panel does not correspond to the expected position. In this case, the tool will also display the panel that should occupy the selected position, helping to quickly identify and correct any mismatches.

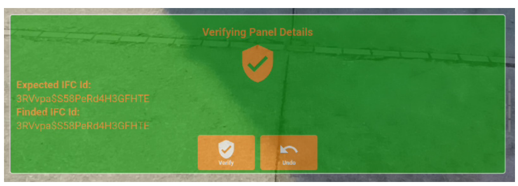

FIG. 16 *Valid panel message.*

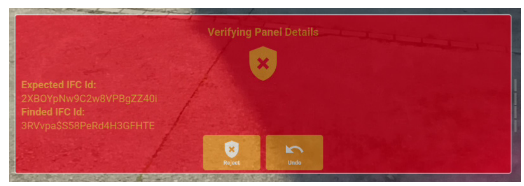

FIG. 17 *Invalid panel message.*

In both cases, whether the panel is valid or invalid, the user will be prompted to confirm the action. Once confirmed, the system will update the DDBB accordingly, automatically refreshing the KPIs and triggering any necessary alerts based on the verification result. Figure 18 shows the coloured digital building with the verified status of the panels. Here, the upper panel is correctly positioned, and the other two are switched.

5 CONCLUSIONS AND FUTURE WORKS

This study presents a practical and accessible solution for enhancing the installation and verification of prefabricated building envelope panels using a cost-effective Augmented Reality (AR) tool. Unlike traditional AR implementations that rely on expensive head-mounted displays and complex BIM file conversions, this tool leverages widely available mobile devices and web technologies (WebXR, Three.js, React) to deliver real-time, on-site guidance without the need for specialised hardware or software installations. The tool eases the repetitive task of installing panels by providing workers with accurate information about the final location of each panel, as well as installation instructions and safety details. This feature helps minimise errors, accelerates the installation and verification process through QR code scanning, and enhances on-site safety.

The tool successfully bridges the gap between digital models and real-world construction environments by overlaying BIM data directly onto physical structures. It supports both installers and managers through dual interfaces, AR-enabled for field operations and standard web-based for project oversight, ensuring synchronised, real-time updates via a centralised database.

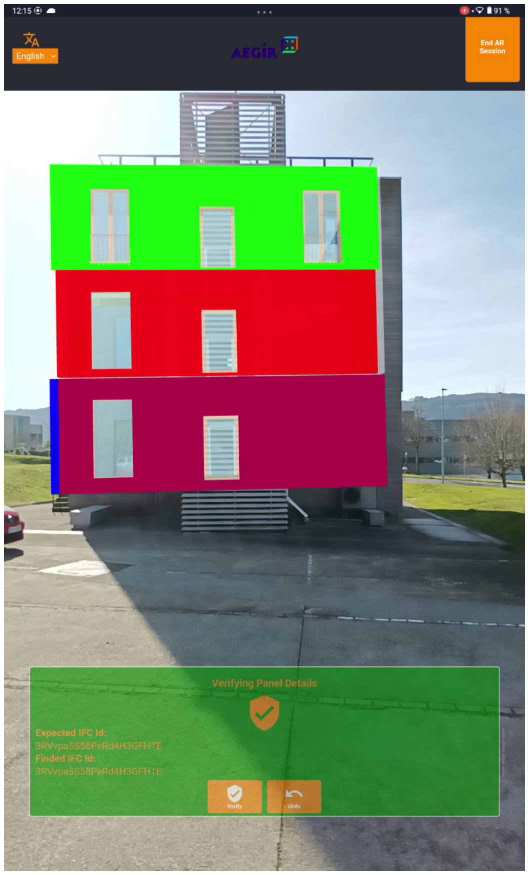

FIG. 18 *Verified panels displayed in AR over the building.*

While the tool is designed to streamline workflows, its actual impact on installation and validation time has not yet been quantitatively assessed. However, by reducing manual data entry, enabling continuous AR sessions, and providing real-time visual guidance, the tool is expected to significantly reduce the time required for these tasks. Future studies should include time-tracking metrics to evaluate these potential gains and validate the tool's effectiveness in improving on-site productivity.

The tool, connected to a centralised database via a RESTful API and WebSocket, allows real-time updates on the status of the installation. This improves communication between operators and managers, facilitates tracking of site progress, and enables more informed decision-making.

In the short term, it would be possible to integrate the capture of images of the installation to document the process (both before and after) from the same device that is being used. Another functionality that the WebXR interface allows is to track the device's movement, so that the movements of both the installer and the validator can be monitored. With this data, subsequent analysis (total validation time, average validation time per panel) could be performed, as well as suggestions or alerts on the movements made. Additionally, and to facilitate interaction, it could be practical to use a module for capturing voice commands, which would reduce the need for interaction with the screen.

In the long term, similar tools could expand their functionality beyond panel installation to include other tasks such as plumbing, electrical, or HVAC systems. In addition, the tools could be integrated with other emerging technologies such as robotics or artificial intelligence.

For example, information from the AR tool could be used to guide robots in performing tasks or to enable the AI to detect errors in real time. The use of artificial vision could avoid having to resort to QR codes in cases where elements to be installed would allow it.

In summary, the proposed tool addresses current limitations in AR use within construction by enabling the direct use of BIM files on mobile devices through WebXR, thereby eliminating the need for costly hardware, complex data conversions, and software installations. It provides real-time guidance and verification for panel installation, improves site communication and efficiency, and has potential for future expansion into other construction tasks and integration with robotics, artificial intelligence, and computer vision.

Acknowledgments

The results and the study described here are part of the results obtained in the AEGIR project: "DigitAl and physical incrEmental renovation packaGes/systems enhancing envIronmental and energetic behaviour and use of Resources" (Cordis, 2022). This information reflects only the author's views, and neither the Agency nor the Commission is responsible for any use that may be made of the information contained therein.

The OpenBIM (IFC) file of the experimental building KUBIK has been used to carry out the entire process outlined below. The various functionalities of the application have been tested as soon as they have been implemented by keeping the test and development environment as close to the final use case as possible (Tecnalia," n.d.).

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