Designing an extended reality platform to optimise operation and maintenance for dynamic building envelopes

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Abstract
This paper presents the design phase of an Extended Reality (XR)-based platform aimed at optimising operation and maintenance for dynamic building envelopes. The proposed solution addresses the growing need for advanced facility management tools that support energy performance and operational efficiency throughout the building lifecycle. The platform integrates heterogeneous data sources, including Building Information Modelling (BIM), Internet of Things (IoT) sensors, and Digital Product Passports (DPPs), to enable real-time fault detection, remote technical assistance, and enhanced communication between key actors. Built on user story methodologies, the platform uses cloud architecture and consumer smart devices to deliver scalable, cost-effective maintenance workflows with XR technology. In addition, Artificial Intelligence (AI) capabilities are integrated to support historical data analysis and automated reporting generation. Preliminary platform validations in real-world environments have demonstrated encouraging results in terms of increased building intelligence, maintenance operation efficiency, and user satisfaction.

Keywords
Extended Reality (XR), Dynamic Building Envelopes, Maintenance Optimisation, Facility Management, User-Centred Design, Smart Buildings

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1 INTRODUCTION

The increasing complexity and operational demands of modern building systems, particularly those that integrate active systems into building envelopes, are opening the way for maintenance and facility management activities to be designed and executed. Dynamic building envelopes (Romano et al., 2018), which include operable façades, automated solar shading systems, intelligent glazing, and building-integrated photovoltaic (BIPV) modules, play an essential role in improving building energy performance and occupant comfort (Giovanardi et al., 2024) (Milardi, 2023). However, their active nature and interdependence with other technical systems, such as HVAC, lighting controls, and shading automation, pose new challenges for long-term operations and maintenance management (Attia et al., 2018; Attia, Lioure, and Declaude, 2020). While these advanced systems promise improved environmental performance and adaptability, maintaining their efficiency over the life of the building is a growing concern and an ongoing challenge. Currently, maintenance practices in the building sector are largely reactive, characterised by manual processes, delayed interventions, and fragmented documentation (Dzulkifli et al., 2021). Unlike sectors such as automotive, aerospace, or manufacturing, where predictive maintenance and digital tools are increasingly integrated into operational strategies (Errandonea, Beltrán, and Arrizabalaga, 2020), the construction and building operations industry has been slower to adopt these advanced digital solutions. Moving forward, the traditional maintenance approach for dynamic building systems, and the Energy Performance of Buildings Directive (EPBD, EU/2024/1275) (European Parliament 2024a) and Smart Readiness Indicators (SRI) framework (European Commission, 2022), imply the need to adopt advanced data-driven management tools. This requires integrating both well-established data sources and interoperable data repositories across various systems and databases. The integration with Building Management System (BMS), Building Energy System (BES), Digital Twin (DT), Building Information Modeling (BIM) using Industry Foundation Classes (IFC) compliant with ISO 16739-1:2024 (ISO 2024a), IoT sensor networks compliant with ISO/IEC 30141:2024 (ISO 2024b), and Digital Product Passports (DPPs), will be an essential condition for creating a comprehensive operational ecosystem where product life cycle information is continuously collected, visualised, updated, analysed, and exploited for driving decision making. Consequently, building technicians require real-time access and visualisation capabilities for effective diagnosis and planning of maintenance interventions.
In this perspective, Extended Reality (XR) applications can play a pivotal role in integrating these multiple data sources and facilitating users' visualisation and understanding, especially for complex systems such as dynamic building envelopes (Bressan et al., 2024). Moving from industries with early adoption applications (Palmarini et al., 2018), also in the construction sector XR has brought to market in the last 5 years a portfolio of products able to support from the design to the construction phases in the building lifecycle, opening the way to investigate the applicability also for maintenance tasks (Faro Technology, 2025; Gamma AR, 2024; Imvizar, 2025; Inception, 2020; Unity, 2024; XYZ Reality, 2023). The experience gained has helped demonstrate the applicability of advances in Virtual Reality, Augmented Reality, and Mixed Reality to different user needs within the construction industry, moving from technical research to products for construction stakeholders.
In recent years, cost reductions, computational improvements, and AI opportunities have accelerated the market introduction of XR technologies and potentialities (Baduge et al., 2022; Mahale et al., 2025; Oulefki et al., 2025; Sadri, 2025; YORD 2024). In this scenario, while predictive maintenance functionalities supported by AI and XR visualisation remain valuable for long-term research and strategic innovation (Reiners et al., 2021), the immediate market focus should prioritise practical, high-utility features to address tangible industry pain points, offering a pragmatic entry point for XR technologies in the building maintenance sector. Building on these premises, this paper details the development, implementation, and validation of an AI-powered XR platform for dynamic envelope maintenance.

The objectives of this paper are to:

- clarify the XR's opportunities (and limits) for maintenance of dynamic building façades;
- present technical and procedural challenges faced during the XR platform's design;
- outline future steps and foster innovative XR tools in the construction sector.

2 METHODOLOGY

This section describes the methods used to conduct the research. A combination of well-established research methodologies and innovative approaches is proposed to design the architecture of the XR platform and the key features to be deployed for market uptake in the field of maintenance for the built environment. The main methodology steps adopted are:

TABLE 1 Research methodology steps

Steps	Activity	Methodology	Deliverable/Outcome
1	**Analysis and classification of dynamic building envelope systems**	Technical Function Analysis (TFA) of dynamic systems and their subsystems. This involves a granular breakdown based on their operational profile, integration level, and lifecycle-specific maintenance requirements.	Categorised Register of Dynamic Systems and associated Maintenance Needs. This list details the critical dynamic components that require proactive monitoring and intervention. See: 3.1, Table 2
2	**Platform requirements and standards definition for maintenance activities**	Stakeholder interviews (semi-structured, focusing on current practices and regulatory compliance) coupled with a systematic review of building standards and EU regulatory frameworks pertaining to operational and maintenance requirements.	Project-specific requirements for the XR platform. These indicators will serve as quantitative metrics for assessing the platform's impact and effectiveness in optimising maintenance processes. See: 3.1, Table 2
3	**Digital infrastructure assessment**	Comprehensive audit of the existing Hardware (HW) and Software (SW) systems utilised for performance monitoring. Includes an in-depth information infrastructure analysis to map data flows within the building's management systems.	Inventory of available sensors and data streams. This output defines the exploitable data resources essential for innovative, data-driven maintenance management and integration with the XR system. See: 3.2, Table 3-4
4	**User stories and requirements analysis**	Qualitative, unstructured interviews with a cohort of 8 key maintenance professionals/ experts, focusing on their expectations, challenges, and perceived benefits (pain/gain analysis) regarding the adoption of innovative tools for maintenance	Functional requirements elicitation. A prioritised list of key functionalities and features to be integrated into the XR platform, derived directly from the documented user needs and operational gaps. See: Table: 5
5	**Platform project framework definition**	User-Centred Design (UCD) methodology implementation for the architectural design and functional specification of the platform. This iterative process ensures the platform features are directly aligned with validated maintenance requirements.	Conceptual XR platform architecture. The final design framework detailing the structure, components, and interface logic of the Extended Reality platform, tailored to enhance maintenance procedures. See: FIG. 1

3 RESEARCH

3.1 FAÇADE SYSTEM ASSESSMENT AND MAINTENANCE REQUIREMENTS

The research conducted focuses on a systematic classification of building envelope systems, identification of the subsystems that contribute to their functionality, and determination of the relevant requirements for both the overall system and its individual components (FIG 1). Dynamic building envelope systems are classified based on their technological components and functional characteristics. Within each system, subsystems that play a key role in the overall performance of the envelope are identified; each subsystem is then analysed based on its technical function, which describes its primary role within the building envelope, and its operational impact, which describes the benefits it provides during the use phase of the building lifecycle. This classification addresses the understanding of each subsystem's contribution to the overall performance of the building envelope. Each building envelope system and subsystem is associated with specific requirements derived from building standards and regulatory frameworks. The activity enabled overcoming the limitations of identifying unique thresholds for maintenance requirements. Indeed, identifying specific requirements for monitoring and maintaining dynamic building envelopes with unique indicators is not possible due to project-specific specifications and national and regional norms that affect the thresholds of reference project by project. For this reason, the XR platform is designed with a multi-source data approach capable to integrate these maintenance requirements moving into specific project Key Performance Indicators (KPIs) during design phase specifications, in use real-time sensor data, and AI-driven benchmarking: these approaches will address the implementation of specific KPIs in the platform at a later stage, during the customisation of the platform for each façade project, currently out of the scope of this design research stage. These requirements ensure compliance with key project performance criteria, such as thermal performance, energy efficiency, durability, air quality, and daylighting. TABLE 2 reports the results of the systems and subsystems classification along with the related maintenance requirements.

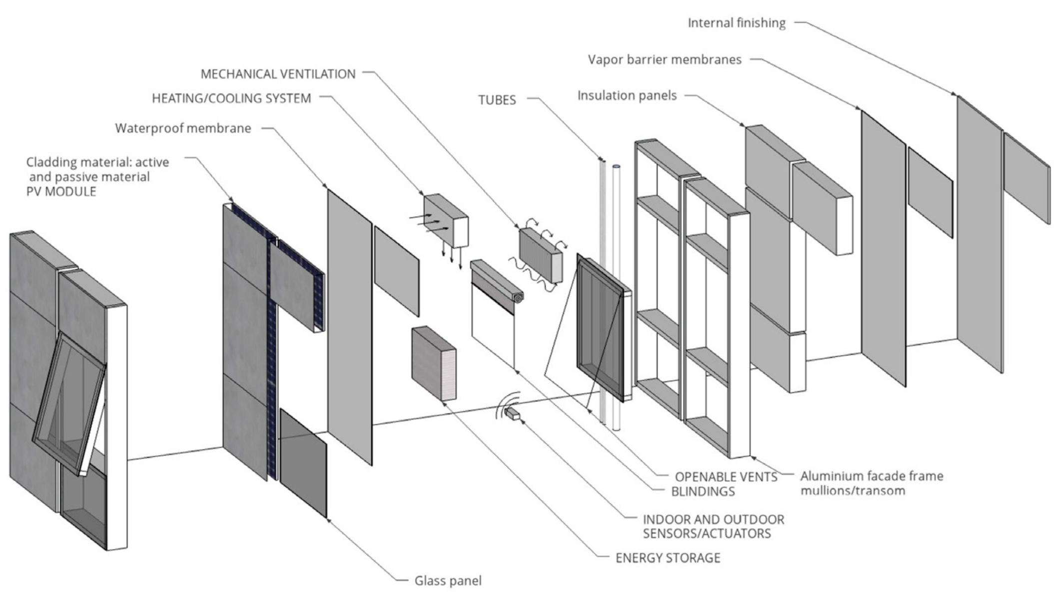

FIG. 1 Multifunctional and dynamic building system (system and subsystem classification). (Giovanardi et al., 2024)

TABLE 2 Requirements definition from the classification of building dynamic envelope systems and subsystems based on norms of reference

Dynamic envelope subsystem	Technical function	Operational impact	Norms to comply with	Maintenance requirements
Blind & actuators	Controls the opening and closing of blinds for shading. Automatically adjusts shading devices based on sunlight and occupancy.	Optimises natural airflow, reducing energy consumption. Enhances energy efficiency and occupant comfort	EN 13363:2008 – Solar protection devices combined with glazing EN 13659:2015 – Shutters and external venetian blinds - Performance requirements including safety	Shading coefficient Safety of components
Window & actuators	Controls the opening and closing of win-dows for ventilation.	Optimises natural light, reducing energy consumption.	EN 12207:2017 – Windows and doors - Air permeability - Classification EN 13659: 2015 – Shutters and external venetian blinds - Performance requirements including safety EN 14351-1:2016 – Windows and external doors (maintenance for operability) EN 12101-2: 2017 – Smoke ventilation windows (if applicable)	Air permeability Safety of components Ventilation rate
BIPV Modules	Generates electricity from solar energy while serving as a building material.	Reduces reliance on traditional energy sources and promotes sustainability.	IEC 62446-1:2016 – Maintenance of PV installations (inspection and testing) IEC 61730-2:2023 – PV module safety tests and periodic checks EN 50583:2016– Maintenance of BIPV systems (specific for building-integrated PV)	Energy generation efficiency Module degradation rate
HVAC Systems	Regulates indoor temperature, humidity, and air quality.	Ensures occupant comfort and health, while optimising energy use.	EN 16798-3:2018 – HVAC ventilation system maintenance requirements ISO 16890:2018 – Air filter maintenance (efficiency degradation) EN 12599:2012 – Performance testing of ventilation systems	Indoor air quality Energy efficiency ratio, Ventilation ratio Filter replacement
Smart Glazing	Adjust tint or opacity to control light and heat transmission.	Improves energy effi-ciency and occupant comfort.	EN 14501:2021 – Solar shading system maintenance EN 673:2011 – Maintenance of smart glazing performance EN 410:2011 – Light transmittance degradation check	Visible light transmittance, Solar heat gain coefficient
IoT Sensors	Collects real-time data on environmental conditions and system performance	Enables proactive maintenance and performance optimisation.	ISO/IEC 30141:2018 – Internet of Things (IoT) reference architecture (maintenance of smart systems) ISO/IEC 27001:2022 – Information Security Management ISO/IEC 27002:2022 – Cybersecurity maintenance of IoT systems	Data accuracy Response time Calibration Software updates Security checks
Air Quality Sensors	Monitors indoor air quality parameters such as CO2, VOCs, and particulate matter	Ensures a healthy indoor environment and compliance with air quality standards.	EN 13779:2008– IAQ monitoring and ventilation maintenance ISO 16000:2021 – Testing indoor air pollutants EN 16798-1:2019 – Energy performance of buildings – Ventilation for buildings	CO2 concentration VOC levels Calibration Filter replacement
Lighting Control Systems	Automatically adjusts lighting levels based on occupancy and daylight availability.	Reduces energy consumption and enhances occupant comfort.	EN 12464-1:2021 – Light and Lighting - Lighting of Workplaces - Part 1: Indoor Workplaces EN 15193:2021 – Energy Performance of Buildings - Energy Requirements for Lighting	Lighting power density (LPD) Daylight autonomy
Energy Management Systems	Monitors and controls energy consumption across various building systems.	Optimises energy use and reduces operational costs.	ISO 50001:2018 – Energy management system maintenance EN 15232:2017 – Maintenance of automation systems for energy efficiency	Energy consumption Energy savings Thermal comfort Calibration

3.2 DIGITAL INFRASTRUCTURE ASSESSMENT

While these maintenance requirements provide a reference for classifying benchmarks of expected building performance at the as-built stage, they do not account for long-term degradation or operational variability in the operative performance of the dynamic building envelope. In fact, for each subsystem and each requirement, the XR platform should include project-specific data inputs for the specific requirement. The values cannot be predefined as static thresholds but must be adjusted based on project-specific conditions and dynamically based on operational performance trends. Baseline values for the XR platform initial setup should use architectural and engineering design data, particularly from BIM models and energy simulations, as well as information on code compliance (e.g. ventilation rates, thermal transmittance or BIPV efficiency). However, beyond this data, integrating real data is key to an effective dynamic façade maintenance platform. For this purpose, data collection from IoT and IT building systems is required to refine the platform functionalities beyond design assumptions by integrating IoT-based monitoring infrastructure, temperature sensors, airflow meters, photovoltaic power output meters, and smart lighting controllers with AI analytics. This data provides a continuous stream of operational parameters, enabling historical performance-based tracking of KPIs. Leveraging the data in this way allows for a more accurate assessment of envelope performance, particularly for identifying early signs of material degradation or efficiency loss. By integrating these advanced AI analytics with the BIM model and XR-enhancement identification, the platform can support KPIs moving from as-built and project-expected impacts to real, performance-driven benchmark identification.

The need to identify real and dynamic benchmarks for façades, as well as to define standards-based maintenance requirements, allows for the identification and implementation of hardware (HW) solutions as data sources for performance monitoring, benchmarking, and compliance verification. For research purposes, these hardware components are usually integrated and consequently analysed in the two possible levels of adoption: at the building level, considering the hardware for IT building systems that can be part of the IT building management infrastructure and the IoT monitoring systems; at the level of hardware for vision-based XR integration systems adopted to fully enable XR platform functionalities. For this purpose, IoT sensors, smart meters, and AI-powered analytics tools facilitate continuous data collection and enable real-time assessment of key metrics, including thermal transmittance, air permeability, shading efficiency, and energy consumption. At the same time, vision-based hardware, including infrared thermographic cameras, high-resolution optical sensors, and hyperspectral imaging systems, improves the detection of material deterioration, water infiltration, and insulation failures, ensuring code compliance. By integrating hardware at both the IT infrastructure and field inspection levels, this approach ensures data-driven decision-making while facilitating future integration with XR-based visualisation and diagnostics for enhanced maintenance workflows. Moving from requirements-based monitoring to technical requirements allows defining functional and non-functional categories: the first for features designed to be useful for the dynamic building envelope, while the second focuses on scalability, security, interoperability with BIM and IoT networks, and compatibility with future XR-based interfaces. TABLE 3 reports the results of the research conducted.

TABLE 3 Identification of hardware to track maintenance requirements for building envelope subsystems and related technical requirements for XR platform design

Maintenance requirements	HW for IT Building Systems	HW for Vision-based XR Integration	Technical Requirements
Thermal transmittance, Thermal resistance, Moisture control	IoT temperature & humidity sensors	Infrared thermographic cameras	XR-enhanced diagnostics XR for data performance visualisation AI-driven predictive maintenance Automated anomaly detection Real-time IoT integration
Structural integrity Weather resistance Material degradation	Load sensors Vibration sensors Acoustic emission sensors	High-resolution cameras	XR-enhanced diagnostics XR for data performance visualisation AI-driven predictive maintenance Automated anomaly detection Automated compliance tracking
Water penetration resistance Moisture resistance UV exposure	IoT humidity sensors	Infrared thermographic cameras Hyperspectral imaging camera	XR-enhanced diagnostics XR for data performance visualisation AI-driven predictive maintenance Automated anomaly detection IoT real-time monitoring
Structural load capacity Fixing strength	Structural strain gauges Load cells	--	XR-enhanced diagnostics XR for data performance visualisation Predictive analytics for load management
Visible light transmittance, Solar heat gain coefficient	Light sensors	Photometric camera	XR for data performance visualisation Automated spectral light analysis Real-time adaptive glazing tracking
Shading coefficient Safety of components	Motor condition sensors Light sensors Automated shading control	Photometric camera	XR-enhanced diagnostics XR for data performance visualisation AI-driven predictive maintenance Real-time motor performance tracking
Air permeability Safety of components Ventilation rate	Window opening sensors Wind sensors Automated ventilation control	Infrared thermographic cameras	XR-enhanced diagnostics XR for data performance visualisation AI-driven predictive maintenance IoT-enabled window actuation tracking
Energy generation efficiency Module degradation rate	Smart PV inverters, Power output sensors, Thermographic inspection tools	Infrared thermographic cameras	XR-enhanced diagnostics XR for data performance visualisation Automated PV efficiency analytics AI-enhanced for degradation tracking AI-driven predictive maintenance
Indoor air quality, Energy efficiency ratio, Ventilation ratio Filter replacement	Airflow sensors CO2 & VOC sensors Smart HVAC control units	Infrared thermographic cameras	XR for data performance visualisation Automated IAQ compliance tracking AI-enhanced ventilation performance analytics
Visible light transmittance, Solar heat gain coefficient	Electrochromic response sensors Smart glazing controllers	Photometric camera	XR-enhanced diagnostics AR for data performance visualisation AI-driven predictive maintenance
Data accuracy Response time Calibration Software updates Security checks	IoT gateways Edge computing devices Smart meters	--	XR-enhanced diagnostics XR for data performance visualisation AI-driven predictive maintenance Real-time motor performance tracking
CO2 concentration VOC levels Calibration Filter replacement	CO2 & VOC sensors	--	XR for data performance visualisation Automated IAQ compliance tracking
Lighting power density (LPD) Daylight autonomy	Lighting sensors Lighting controller Occupancy sensors	Photometric camera	XR-assisted overlays for lighting distribution analysis
Energy consumption Energy savings Thermal comfort Calibration	Smart meters AI-based energy analytics tools	--	XR-driven dashboard for energy use visualisation

The study identifies hardware tools that enable effective requirements tracking and XR maintenance. These tools are categorised based on their ability to collect, process, and display KPI-related information to enable efficient defect detection, decision-making, and compliance tracking for building envelopes. These include: wearable devices (e.g. AR visors and smart glasses for field diagnostics), handheld devices (e.g. tablets and mobile devices for real-time monitoring), sensor-based tools, computer vision cameras for defect detection, and environmental sensors for façade performance analysis.

The systematic classification of building envelope systems and their subsystems, along with the definition of maintenance requirements and platform-specific technical requirements, informs the evaluation of commercially available XR hardware for remote maintenance applications to determine the most appropriate solution, focusing on hands-free operation, integration capabilities, ergonomics, cost, and software support. The analysis compared on-market products such as Meta Quest 3, Magic Leap 2, HoloLens 2, and tablet-based solutions to assess the feasibility of augmenting maintenance operations with digital overlays, IoT integration, and real-time support (TABLE 4). One key requirement for maintenance activities is hands-free interaction, enabling technicians to operate tools and perform repairs while receiving real-time digital guidance.

TABLE 4 Analysis of devices in the market for the XR maintenance platform

Device Feature	Meta Quest 3	Magic Leap (1 or 2)	Microsoft HoloLens 2 (Discontinued in many markets)	Tablet
Form Factor	Standalone VR/XR headset (hands-free)	AR headset (hands-free)	AR headset (hands-free)	Handheld device (must be held or placed on a stand)
Display & Field of View (FOV)	High-resolution LCD; improved FOV vs. Quest 2 (~110° rumored)	FOV ~70° (ML2), ~50° (ML1)	FOV ~52°	Standard 2D screen (no immersive FOV)
Tracking	Inside-out 6DoF (built-in cameras & sensors)	Inside-out 6DoF (built-in cameras & sensors)	Inside-out 6DoF (built-in cameras & sensors)	No spatial tracking (touchscreen or stylus input)
Controllers / Input	Touch controllers + hand tracking	Controller + hand tracking	Hand tracking, voice, clicker	Touchscreen (can add external accessories)
OS & Development Ecosystem	Meta-specific Android-based OS; Unity/Unreal engine; robust Meta SDKs & ecosystem	Lumin OS; Unity support; smaller ecosystem than Meta	Microsoft Windows Holographic (UWP-based); older SDK, uncertain future support	iOS / Android / Windows; large ecosystem but not MR-centric
Integration Capabilities	Extensive SDKs (Unity, OpenXR, WebRTC); can integrate external cameras & IoT devices	Some enterprise support, but less flexible for external sensors; higher enterprise pricing	Possible but complicated; limited new hardware features; uncertain roadmap	Runs mobile or desktop apps; can connect to external devices, but no hands-free AR/VR
Ergonomics	Lighter, improved balance compared to Quest 2; designed for comfort	Magic Leap 2 improved over ML1 but can still feel bulky	Higher weight and form factor; can be uncomfortable for extended use	Depends on size/weight; typically held in hands, not worn
Price (Approx.)	USD 500–600 range (consumer/enterprise bundles differ)	USD 3,299–4,999 (ML2); ML1 similarly high priced	Originally USD 5,000+ (enterprise); supply and updates uncertain	Wide range: USD 300–1,000+ (no MR functionality)
Hands-Free Operation	Yes (fully self-contained headset)	Yes (headset, sometimes external compute pack)	Yes (single headset unit)	No (held or placed on a stand, not head-worn)
Discontinued / Ongoing Support	Actively supported by Meta; new features & updates expected	Magic Leap 1 discontinued; Magic Leap 2 still supported but niche enterprise market	No new major updates; limited support. Discontinued	Continuously updated, but not for immersive mixed reality
Overall Suitability for Remote Maintenance	High (robust ecosystem, hands-free, relatively affordable, ergonomic)	Medium (enterprise focus, higher cost, narrower ecosystem)	Medium-Low (expensive, uncertain roadmap, heavier device)	Low for MR (limited AR/VR features, must be handheld)

The Meta Quest 3 and HoloLens 2 provide full head-mounted display (HMD) capabilities, eliminating the need for handheld controllers or tablet interfaces. Compared to the Magic Leap 2, which has a more limited field of view, and tablets, which require constant manual handling, the Quest 3 was found to be the most ergonomic solution for long-term industrial use. As defined in the technical requirements and hardware identification, the XR platform requires seamless integration with infrared thermal cameras, IoT sensors, and AI-driven predictive maintenance analytics. The Meta Quest 3 was found to support external sensor integration via WebRTC, custom APIs, and direct Unity plugins, making it compatible with the XR platform's AI-based diagnostic framework. HoloLens 2 also offers sensor integration but is significantly more expensive and primarily optimised for enterprise-controlled environments rather than open industrial ecosystems. Ergonomics plays a critical role in extended maintenance sessions, where prolonged device use can lead to discomfort or fatigue. The Meta Quest 3 demonstrated a significant improvement in weight distribution compared to its competitors, making it better suited for extended use in construction and facility management scenarios. The HoloLens 2, while offering high-end AR capabilities, remains bulkier and heavier, potentially impacting field usability. From an economic perspective, the affordability of Meta Quest 3 makes it a viable option for large-scale deployment within the XR platform. While Magic Leap 2 and HoloLens 2 offer enterprise-grade capabilities, their higher cost limits scalability for widespread maintenance applications. Tablet-based solutions, while cost-effective, lack spatial awareness and hands-free usability, making them less suitable for real-time XR-driven diagnostics. The XR platform architecture integrates cloud-based data processing, AI-driven diagnostics and real-time collaboration. The Quest 3 aligns well with the XR tech stack, leveraging:

- Unity and OpenXR SDKs for full 3D visualisation and AR overlay capabilities;
- Cloud service (adopted AWS) and WebRTC-based real-time communication, supporting remote assistance and AI-driven predictive maintenance;
- Database storage (adopted MongoDB), enabling real-time maintenance history tracking and failure analysis.

Based on the hardware analysis, Meta Quest 3 was identified as the most suitable XR hardware for the XR platform, balancing cost, ease of use, integration capabilities, and ergonomics. Future research will focus on enhancing AI-driven fault detection and expanding IoT integrations to ensure that XR visualisation provides real-time insights for predictive maintenance in dynamic building envelopes.

3.3 USER STORIES, USER REQUIREMENTS AND TECHNICAL REQUIREMENTS

The user stories research was conducted with 8 senior professionals with more than 10 years of experience in their respective fields. The distribution of participants included: bank loan and insurance underwriters (user: *Building Certification Auditor*); building occupants (user: *Building Occupant*); facility managers (user: *Facility Manager*); façade designers and professional practitioners, and maintenance technicians (user: *Façade Technicians*). All these actors were also asked to suggest new features as end users of the building. This sample, while not considered consistent in terms of market size, provided a broad perspective on various aspects of façade design, maintenance and operations, while ensuring that participants had significant expertise in their fields, with a focus on residential and commercial building maintenance sectors and public real estate operations. Interviews were conducted over a four-week period via direct mobile phone calls or face-to-face meetings, with each session lasting approximately 40-60 minutes.

TABLE 5 User stories identification for user requirements and technical requirements definition.

As a... (Type of User)	I Want to... (Perform a Task)	So That I Can... (Achieve This Goal)	User Requirement	Technical Requirement	Functionalities
Building Certification Auditor	Take standardised photos for certification	Meet certification documentation requirements	Guided photo capture system	AR-enhanced photo capture and visualisation AR-enhanced checklists	Improvement in photo accuracy
Building Certification Auditor	Generate certification-compliant reports	Submit accurate certification applications	Template-based report generation	AI-powered automated reporting Integration with certification requirements Validation system	Reduction in report generation time
Building Certification Auditor	Take photos, take notes, upload documents and generate template-based reports	Create standardised documentation efficiently	Mobile-friendly photo capture and report generation	AR-enhanced photo capture and visualisation Template management system AI-powered automated reporting	Reduction in report generation time
Building Certification Auditor	Collect and verify building performance data	Complete efficient certification audits	Collect certification documents/data in line with checklist	AR-enhanced checklist Integration with certification requirements Data validation system Automated data collection and verification tools	Reduction in audit time
Building Occupant	Report maintenance issues	Get timely understanding of facility problems	Simple issue reporting procedure Fast communication with maintenance	Mobile/Web-based issue reporting and ticketing system	Improvement in user satisfaction for issue reporting
Building Occupant	Get in contact with technician	Solve technical problems efficiently	Direct contact with technician	AR-enabled real-time remote support Real-time data monitoring and processing Secure high-speed data transmission and communication logging	Reduction in maintenance time
Building Certification Auditor	Document and report findings from the inspection	Generate a comprehensive and standardised SRI assessment report	Generate SRI report and assess score	AI-powered automated reporting	Reduction in report generation time
Facility Manager	Access historical maintenance records	Track building performance and maintenance costs	Comprehensive maintenance history dashboard	AI-powered predictive maintenance AI-based fault detection system Cloud-based structured database for records Data visualisation tools	Increase in cost tracking accuracy
Facility Manager	Monitor real-time energy consumption and performances	Optimise building energy performance	Energy usage dashboards with trend analysis	AI-driven energy performance analytics Long-term trend visualisation Integration with building digital systems (BIM, IoT, BMS, BEM) Automated real-time system tracking Real-time data monitoring and processing	Reduction in energy consumption
Facility Manager	Access real-time building performance data	Make informed decisions about maintenance scheduling	Easy-to-use dashboard with key performance metrics	Integration with building digital systems (BIM, IoT, BMS, BEM) Data visualisation tools	Reduction in extraordinary maintenance intervention
Facility Manager	Know previous maintenance activities on a system when a new technician takes over	Ensure continuity and efficiency in maintenance interventions	Access past interventions	Cloud-based structured database for records AR-enhanced visualisation of maintenance records	Reduction in maintenance time
Facility Manager	Ensure maintenance technicians follow building systems recommended checklists	Perform maintenance as required by the manufacturer for compliance and safety	Provide access to maintenance manuals and checklists	AR-enhanced checklists	Reduction in unexpected system failures
Facility Manager	Ensure maintenance manuals are easy and up to date	Reduce inefficiencies caused by lost or unused documentation	Store manuals in a central repository that is easily linked to building systems.	Cloud-based document storage and tagging system Digital tagging of manuals via QR codes, NFC, AR overlays	Increase in checklist compliance rate
Facility Manager	Track past interventions, materials used, dates, and companies responsible	Improve accountability and long-term maintenance planning	Digital intervention records with searchable logs	AI-powered automated reporting Cloud-based structured database for records	Reduction in maintenance time Improvement in maintenance tracking accuracy

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TABLE 5 User stories identification for user requirements and technical requirements definition.

As a... (Type of User)	I Want to... (Perform a Task)	So That I Can... (Achieve This Goal)	User Requirement	Technical Requirement	Functionalities
Facility Manager	Receive automatic notifications for required maintenance and access contact information for service providers	Ensure timely interventions and provide necessary documentation to technicians	Maintenance reminders with direct links to service provider contacts and manuals	AI-powered predictive maintenanceAI-driven maintenance scheduling systemIntegration with building digital systems (BIM, IoT, BMS, BEM)Cloud-based structured database for records	Reduction in unexpected system failures
Facility managers	Take photos, take notes, upload documents and generate template-based reports	Create standardised documentation SRI	Mobile-friendly photo capture and report generation	AR-enhanced photo capture and visualisation Template management system AI-powered automated reporting	Reduction in report generation time
Facility managers	Collect detailed information on building systems and technologies installed	Verify the building's smart readiness level according to SRI criteria	Track accurate and up-to-date data on installed technologies (HVAC, lighting, automation systems, etc.)	AI-powered automated reporting AR-enhanced checklists for SRI assessment Automated SRI scoring system	Reduction in report generation time Improvement of accuracy in reporting
Facility managers	Verify the operational status of smart building functionalities	Assess compliance with SRI-defined indicators and scoring	Tools for real-time status checks of systems (e.g. IoT-enabled HVAC, energy meters)	AR-enhanced checklists for SRI assessment SRI score calculation Real-time data monitoring and processing	Number of validated functionalities inspected
Façade technician	Diagnose technologies issues	Improve first-time fix rates	Identify in a short time problem and technology to work for	AI-based fault detection system Integration with building digital systems (BIM, IoT, BMS, BEM) Data visualisation tools AR-enabled diagnostic tools	Increase in first-time fix rate
Façade technician	Generate standardised maintenance reports	Ensure compliance with maintenance procedures	Automated report generation with maintenance procedures	Integration with maintenance procedures AI-powered automated reporting	Reduction in report generation time
Façade technician	Avoid unnecessary trips to answer customer calls	Solve/define technical problems efficiently	AR remote assistance capability	AR-enabled real-time remote support Secure high-speed data transmission and communication logging	Reduction in extraordinary business trip
Façade technician	View and complete maintenance procedure checklists	Complete repairs efficiently and accurately	AR interface with access to maintenance instructions	AR-enhanced document visualisation and interaction	Reduction in maintenance time Reduction in extraordinary maintenance intervention Increase in checklist compliance rate
Façade technician	Maintain the building envelope	Know where and how to maintain technologies	Access to technology information and documentationDocument access paperless	Technology identification for efficient maintenance AR-enhanced document visualisation and interaction Cloud-based structured database for records AR-enhanced visualisation of maintenance records	Reduction in maintenance time Reduction in documents loss
Façade technician	Identify building technologies	Recommend improvements to optimise performance	Ability to compare current performance with optimal SRI scoring requirements	AI-powered performance simulations AI-powered predictive analytics AI-driven recommendations for enhanced smart readiness performance	Number of actionable recommendations generated Improvement of SRI score

3.4 XR PLATFORM ARCHITECTURE DESIGN

The architecture of the XR platform for the dynamic building envelope is designed in line with user requirements and technical requirements defined. Based on the technical requirements identified, the architecture of the platform is structured around four components:

- Data source. This layer acquires real-time data from multimodal sensors, IoT networks, and digital building models to monitor the dynamic building envelope system and its subsystems. It integrates thermal imaging, hyperspectral analysis, photometric data, and structured building information from IT systems installed and running in the building, such as IoT network, BIM, BMS, BEM, and DPP.
- Data interoperability. This layer standardises and consolidates data streams through a scalable data lake and multi-tier communication framework. It ensures real-time synchronisation between distributed databases, BIM models, and digital twins, and provides structured data pipelines for analysis. The communication layer enables interoperability between sensor networks, XR devices, and BMS platforms, supporting low-latency data exchange and remote access. This layer includes integrating Business Intelligence tools, dashboards, and KPI tracking to enhance decision-making, supporting proactive maintenance and sustainability compliance.
- AI services. This layer AI features are based on user requirements for predictive analytics, automated reporting, compliance validation, and anomaly detection to optimise the building envelope. AI-driven models process historical and real-time data to generate insights for dynamic building envelope management and failure forecasting.
- XR Platform. This layer provides users with interfaces that support insight analysis, remote assistance, on-site immersive visualisation, and interactive analysis through AR-enhanced dashboards and visor-based interfaces. Real-time sensor overlays, AI-driven insights, and 3D model integrations facilitate fault diagnosis, dynamic building envelope performance assessment, and user-driven optimisation. The visualisation engine processes high-resolution geospatial data for augmented monitoring, remote inspections, and AI-driven adjustments.

The development phase of the XR platform focused on implementing a user-centric front-end dashboard, designed to support the practical implementation of user stories and align with the broader architectural framework of the platform. The dashboard design emphasises visual clarity and logical organisation to minimise the learning curve for both technical and non-technical users. Relevant data, such as maintenance records, real-time performance indicators, system alerts, and 3D model visualisation, are easily accessible without overwhelming the user with unnecessary information. Reducing interface clutter directly supports faster decision-making and operational efficiency. Special attention was given to accessibility and usability across multiple devices. The dashboard follows universal design principles to ensure consistent functionality and readability across a range of screen sizes, from head-mounted XR devices to tablets and standard desktop displays. This device-agnostic design ensures that technicians in the field, facility managers in control rooms, and external auditors can seamlessly interact with the platform regardless of their technology environment. A key feature of the dashboard is its collaborative environment, designed to facilitate communication between remote experts and on-site operators. Integrated chat features, annotation tools in shared augmented reality environments, and real-time remote assistance capabilities allow multiple stakeholders to effectively share knowledge, support rapid problem resolution, and improve operational coordination. Interventions are tracked in real-time via AI-enabled reporting. These collaborative tools were mapped directly from user story input that highlighted the need for remote technical support and transparent sharing of maintenance documentation.

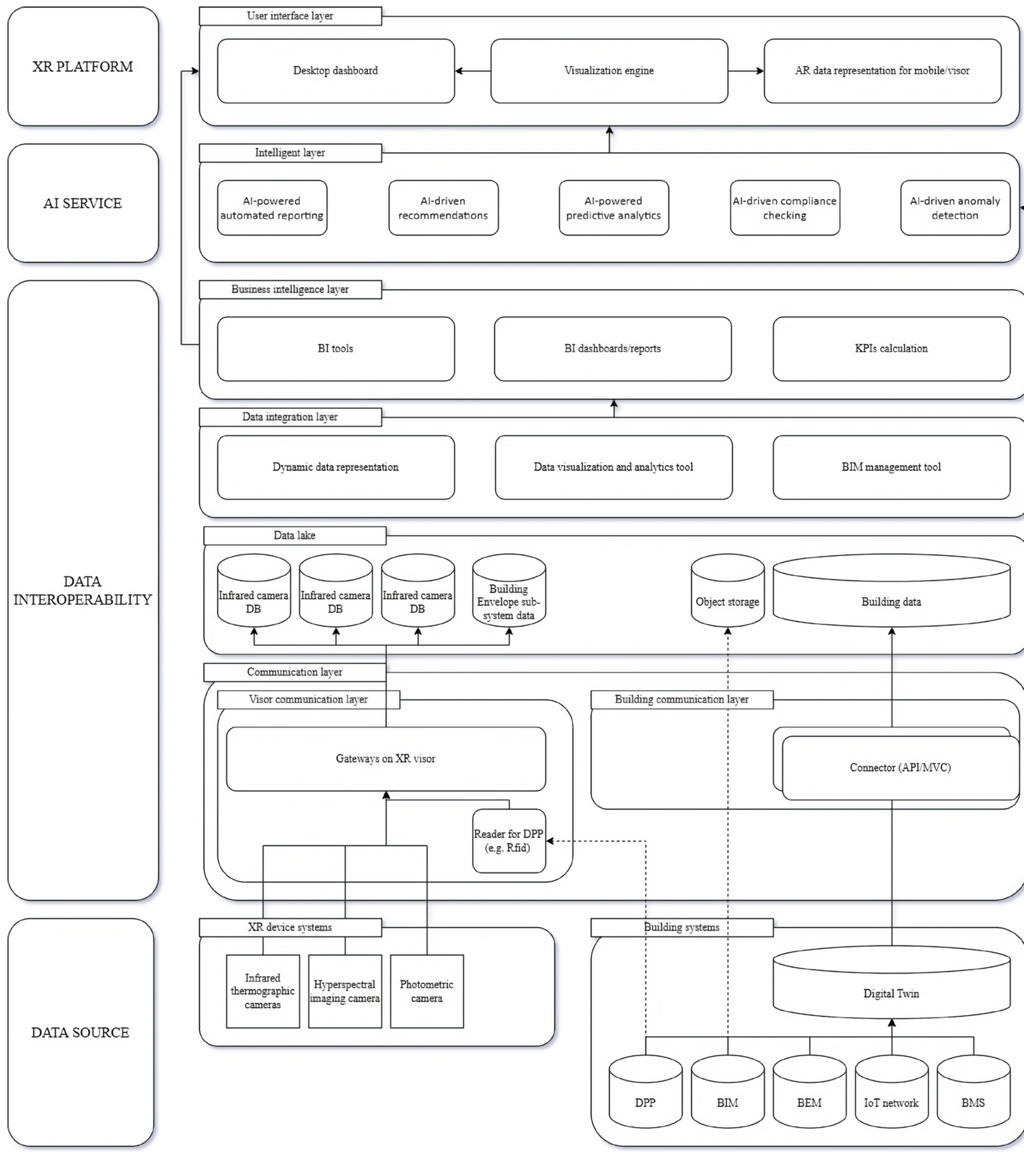

FIG. 2 XR platform architecture

4 RESULTS

The results and analysis of user stories and direct input from facility management stakeholders revealed several critical pain points that impact maintenance efficiency and knowledge transfer. One of the most significant challenges is the lack of structured maintenance history tracking, which creates knowledge gaps when new technicians take over a system, leading to inefficiencies and repeated interventions. In addition, despite the availability of maintenance manuals and technical guidelines, technicians are often reluctant to use them, either due to time constraints, lack of accessibility, or reliance on experience-based troubleshooting. This results in inconsistent maintenance practices, reducing the effectiveness of interventions and impacting the long-term performance of building components. A key requirement emerging from these findings is the opportunity for digitalisation of maintenance records, ensuring that interventions, material usage, and service provider details are systematically logged and accessible. By integrating these functionalities into an XR-enhanced maintenance platform, users can quickly access maintenance histories, receive guided procedures, and visualise past interventions within the building environment. Addressing these user needs through intuitive digital documentation, AI-powered recommendations, and seamless AR access to maintenance data represents a critical step toward optimising dynamic building envelope management and enhancing technician workflow efficiency.

FIG. 3 Maintenance technician using the headset to access the XR platform during the validation phase.

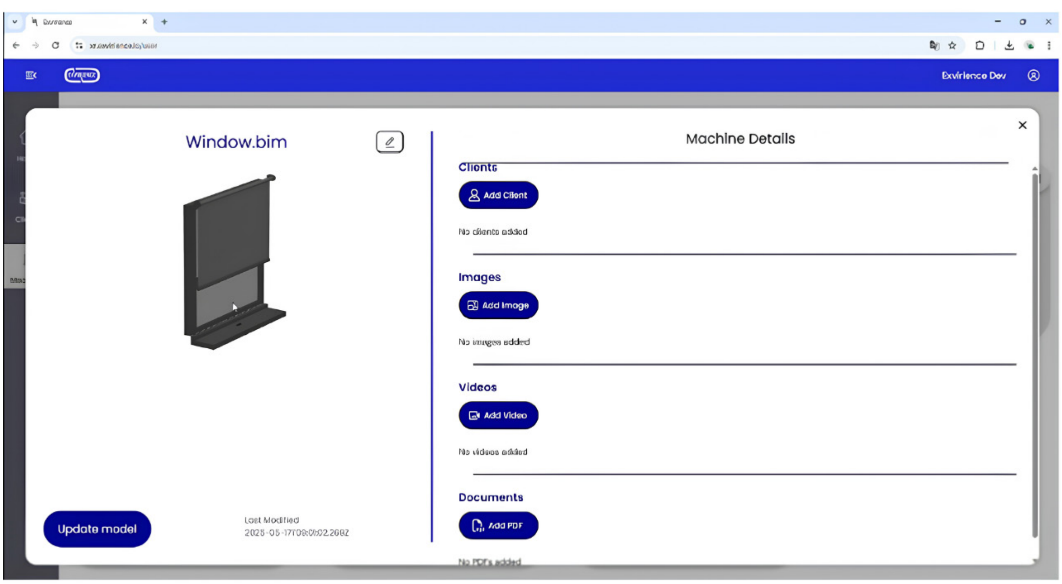

FIG. 4 The XR platform main dashboard, accessible via web.

In the proposed platform design, requirements for dynamic building envelope subsystems should move from qualitative measures to precise numerical values that reflect both design-phase inputs and as-built performance data. Numerical values are consequently project-based and derived from baseline values established during the design phase and should be further refined through continuous AI analysis of historical data collected via IT building systems, IoT devices, and AR-enhanced visual inspections. Using machine learning algorithms such as regression models and clustering techniques, the system compares current maintenance and performance levels against design specifications, enabling real-time anomaly detection and predictive maintenance scheduling.

FIG. 5 Visor XR platform functionality: real-time drawing for easy communication with remote technicians. Picture from the visor used by the operator.

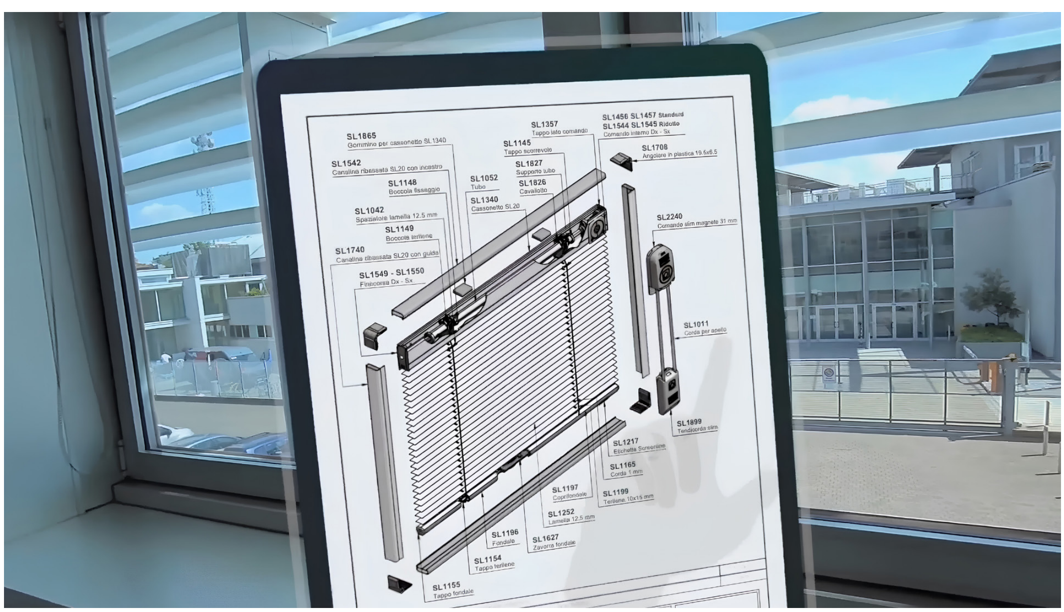

FIG. 6 XR platform functionality: visualisation of technical datasheets overlaying the real environment. Picture from the visor used by the operator.

This methodology not only could support the identification of underperforming components but also facilitates targeted maintenance interventions before critical failures occur. These methods provide a multifaceted framework for continuous performance improvement. Ultimately, this integrated approach supports a robust, data-driven maintenance strategy that increases asset longevity and operational efficiency. This implementation requires historical data for advanced analytics, which should be a major focus in the next phases of XR development. However, the results confirmed that platform KPIs must be treated as adaptive variables, continuously recalibrated through AI-driven analysis and real-time monitoring.

FIG. 7 XR platform functionality: vocal and video call for remote technical assistance.

FIG. 8 XR platform functionality: maintenance report automatic generation.

The XR-based platform benefits from this dynamic framework by highlighting underperforming components in real time through AR overlays, triggering predictive maintenance alerts when deviations exceed machine-learning-calibrated thresholds, and improving technician decision-making by providing an AI-optimised reference for expected system performance. In addition, integrating AI algorithms allows for the development of specific functionalities tailored to the type of façade.

Based on the XR platform design research activity, an early-stage deployment of the platform was conducted to evaluate the research outcomes for the proposed case study. The deployment focused on the recurring functionalities of maintenance activities, namely the ability to view technical documents, establish a remote connection with a technician and generate automatic reports. The implemented platform is used for the initial design evaluation phase with stakeholders. (FIG. 3-8)

5 DISCUSSION

This study establishes a comprehensive conceptual and architectural foundation for an XR-based platform dedicated to optimising maintenance within dynamic building envelopes. The adopted methodology, which integrates TFA with a UCD approach, has successfully enabled the definition of the platform's technical and functional requirements in direct response to concrete operational needs within the sector. The small sample size (n=12) should be considered when generalising the findings. Even though this could represent a limitation to demonstrate market scalability of the XR platform, in this design stage, the user stories are considered satisfactory for the depth of experience (>10 years) of the participants, and their diverse roles provide valuable insights into façade maintenance operations and requirements across different building types. In fact, this includes users engaged in residential and commercial buildings and public facilities, while industrial buildings were specifically excluded from the scope of the study to maintain the focus on civil infrastructure maintenance needs. The result highlighted three primary capabilities required across user groups:

- Remote collaboration:
  - real-time remote support;
  - guided remote inspections;
  - remote document access and sharing.

- Documentation management:
  - standardised report generation;
  - template-based documentation;
  - historical record tracking;
  - document verification and validation.

- Performance monitoring:
  - real-time system monitoring;
  - predictive maintenance alerts;
  - environmental performance tracking;
  - energy consumption monitoring.

These results indicate a strong emphasis on operational efficiency and maintenance optimisation, with XR technology serving as a key enabler for remote collaboration and on-site task execution. The analysis identified the following requirements classification for measuring platform success:

- Time reduction metrics:
  - reduction in maintenance time;
  - reduction in report generation time;
  - reduction in compliance verification time;
  - reduction in extraordinary maintenance interventions.

- Accuracy improvements:
  - increase in assessment accuracy;
  - improvement in photo accuracy;
  - increase in cost tracking accuracy;
  - improvement in maintenance tracking accuracy.

- Efficiency gains:
  - increase in first-time fix rate;
  - reduction in unexpected system failures;
  - increase in checklist compliance rate;
  - reduction in documents loss.

The technical requirements analysis allows clustering of several key technology areas to implement user requirements and monitor:

- XR integration:
  - XR-enhanced photo capture and visualisation;
  - XR-enabled real-time remote support;
  - XR-enhanced checklists and measurement tools;
  - XR interface for maintenance instructions.

- Data management and integration:
  - cloud-based structured databases;
  - integration with building digital systems (BIM, IoT, BMS, BEM);
  - document tracking and validation systems;
  - real-time data monitoring and processing.

- AI components:
  - AI-powered automated reporting;
  - AI-driven recommendations;
  - AI-powered predictive analytics;
  - AI-driven compliance checking.

6 CONCLUSION

The research addressed the growing complexity of dynamic building envelopes by proposing a multi-layered XR platform designed to optimise maintenance workflows. The research confirms the possibility and feasibility of dynamic maintenance of the building envelope using XR, and the correctness of the methodological approach. This seems particularly relevant given the increasing pace of digitalisation in the construction sector and the need for a method to move from research to the market. By synthesising the findings from the design and user-validation phases, the conclusions can be structured around the following key pillars.

6.1 OPPORTUNITIES AND LIMITS OF XR FOR DYNAMIC BUILDING FAÇADES.

The study clarifies that the primary opportunity offered by XR technology lies in its ability to act as a "digital glue", merging BIM, IoT, and DPP data into a unified immersive interface. This integration provides technicians with real-time diagnostic information directly on-site, significantly reducing cognitive load and errors. However, while the integration of XR platforms with AI-driven predictive maintenance is a promising research direction, its practical adoption in the building sector remains limited due to the industry's slow digital transition, long asset lifecycles, and fragmented data management practices, as emerged during user stories interviews. Unlike sectors such as automotive or aerospace, where real-time sensor data and predictive analytics are well established, the lack of widespread IoT adoption and smart metering for building envelopes limits the viability of data-driven maintenance strategies. As a result, while the research field continues to develop advanced AI-assisted diagnostics and XR-enhanced visualisation tools, these capabilities are not yet a market-ready driver for XR adoption in the built environment, and the slowness of digital technology for the built environment does not hold promise for moving from research to market adoption, if not in niche building environments. At this stage, the research demonstrates that the most viable approach to adopting the XR platform should focus on simpler yet valuable capabilities that integrate AI features to address immediate façade management needs, such as tracking maintenance interventions, managing digital maintenance records, and generating automated reports to support regulatory compliance. These features provide a clear value proposition by streamlining documentation, reducing operational inefficiencies, and ensuring maintenance traceability over time, thus lowering the barrier to entry for facility management digitisation.
By prioritising practical, scalable features over long-term predictive maintenance capabilities, the XR platform can accelerate market entry and lay the foundation for future data-driven and AI-enhanced maintenance ecosystems as IoT adoption matures for dynamic building envelopes and the entire building.

6.2 TECHNICAL AND PROCEDURAL CHALLENGES IN XR PLATFORM DESIGN

The designed XR platform establishes a future-proof maintenance framework for dynamic building envelopes, maximising SRI scoring potential while improving energy efficiency, automation, and data-driven decision making. The design process highlighted that the greatest technical challenge is ensuring seamless data interoperability between heterogeneous sources (real-time sensors and static databases). To overcome this, the paper proposes a cloud-based architecture that prevents data silos. From a procedural standpoint, the study emphasises that a UCD approach is mandatory. The challenge lies in translating complex technical maintenance requirements into intuitive user stories, ensuring that the technology supports, rather than hinders, the operator's manual tasks. While user stories effectively guided the architectural definition, and preliminary software and hardware demonstrations validated technical feasibility, the next critical phase involves transitioning from theoretical development to empirical validation through on-field applications. This progression is pivotal for moving beyond conceptual and research-oriented investigations, particularly within the underexplored domain of dynamic building envelopes. Demonstrating the operational performance of XR platforms through real-world case studies will allow for the quantification of KPIs related to maintenance efficiency, time and cost optimisation, and improved access to historical data. Such metrics are essential not only for operational benchmarking but also for substantiating the economic and managerial value proposition of adopting XR technologies in construction asset management.

6.3 INNOVATION AND THE FUTURE OF THE CONSTRUCTION SECTOR

The research fosters innovation by demonstrating how AI-driven features (such as automated reporting and fault detection) can transform XR from a simple visualisation tool into a proactive decision-support system. This shift is crucial for the construction sector to transition from reactive to predictive maintenance models. By using consumer-grade hardware such as the Meta Quest 3, the proposed framework proves that high-level digital twinning is becoming economically accessible, paving the way for a broader adoption of "Smart Readiness" protocols in facility management. Future research will focus on empirical demonstrations to validate whether integrating multi-source data, advanced visualisation, and decision-support functionalities within XR platforms can deliver measurable benefits over conventional digital tools. In particular, the capability to enable non-specialised personnel to perform maintenance operations with precision and ensure systematic tracking across the entire service life of façade systems presents a significant innovation pathway for the sector.

6.4 FUTURE STEPS AND RESEARCH OUTLOOK

Moving forward, the research will focus on the large-scale implementation of this platform to validate its scalability across different building typologies. Further studies are required to assess the long-term ergonomic impact on workers and to refine the AI algorithms for even more precise anomaly detection. The ultimate goal remains the standardisation of "XR-ready" digital handovers, ensuring that every dynamic façade is delivered with a functional, accessible Digital Twin throughout its lifecycle. The findings of this study underline the strategic importance of digital augmentation in the management of increasingly complex building systems, particularly dynamic façades. The proposed XR platform lays the groundwork for elevating the smartness level of dynamic building envelopes, a segment historically underserved by digital maintenance solutions, thereby contributing to the broader objectives of sustainability, operational resilience, and lifecycle performance optimisation in the built environment.

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