Građevinski materijali i konstrukcije
Building Materials and Structures

journal homepage: www.buildingmaterialsstructures.com

https://doi.org/10.5937/GRMK2600012C

Review paper

Integrating virtual reality, augmented reality, and artificial intelligence for circular and sustainable construction practices

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Article history

Received: 29 November 2025
Received in revised form: 03 April 2026
Accepted: 20 April 2026
Available online: 11 May 2026

Keywords

artificial intelligence,
virtual reality,
augmented reality,
sustainability,
construction industry

ABSTRACT

The increasing demand for sustainable and efficient construction practices has accelerated the adoption of advanced digital technologies across the sector. This paper presents a conceptual framework based on a systematic theoretical review of the combined potential of Artificial Intelligence (AI), Virtual Reality (VR), and Augmented Reality (AR) to transform construction workflows and support the transition to circular, resource-efficient building practices. VR enhances design comprehension and stakeholder communication through immersive visualization, while AR enables real-time onsite guidance and augmented inspections, improving accuracy and reducing execution errors. Complementing these capabilities, AI introduces predictive analytics, automated defect detection, and data-driven optimisation of materials, labour, and lifecycle performance. By integrating these technologies into a unified digital ecosystem, construction projects can significantly reduce waste, improve quality, and strengthen decision-making throughout the project lifecycle. The proposed conceptual framework illustrates how immersive environments and intelligent analysis can operate in synergy to support sustainability objectives, including lifecycle extension, improved resource efficiency, and alignment with circular economy principles. No empirical component is included; empirical validation of the framework in real construction projects is identified as a primary direction for future research. This study contributes to the ongoing digital transformation of the construction industry by articulating a holistic, lifecycle-spanning perspective on integrating VR, AR, and AI, providing a replicable foundation for future research and practical implementation.

1 Introduction

The construction industry is undergoing a crucial period of transformation driven by the global demand for sustainable development, increased efficiency, and the integration of advanced digital technologies. Historically characterized by high material consumption, fragmented communication, and limited real-time control, the construction sector continues to face challenges, including cost overruns, delays, rework, and significant environmental impacts [1]. The growing complexity of infrastructure projects, stricter regulatory requirements, and global commitments to carbon reduction and resilient urban development further intensify these issues. As a result, the traditional workflows and methodologies used in construction are no longer sufficient to meet modern performance expectations [2].

Digital transformation has emerged as a strategic pathway to address these persistent challenges. Over the past decade, the adoption of Building Information Modeling (BIM) [3]Sensors, simulation tools, and data-driven management systems have laid the foundation for more intelligent, connected project environments. However, the recent rise of immersive technologies, such as Virtual Reality (VR) and Augmented Reality (AR), and advances in computational intelligence through Artificial Intelligence (AI) have accelerated this evolution [4]. These technologies collectively offer the potential to redefine how construction projects are planned, monitored, and executed.

VR provides fully immersive, computer-generated environments that allow stakeholders to explore and interact with virtual models before construction begins. This capability improves design understanding, supports design validation, and enables early detection of conflict areas that might otherwise go unnoticed. AR, on the other hand, enriches real-world jobsite conditions with digital content, projecting BIM elements onto physical environments to facilitate real-time inspections, quality control, and more

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accurate assembly and installation processes [5]. These immersive tools significantly enhance communication and collaboration among architects, engineers, contractors, and clients by making complex information more accessible and understandable.

AI complements VR and AR by enabling automation, prediction, and real-time decision-making. Machine learning and computer vision techniques can analyze large volumes of visual and numerical data to detect defects, evaluate construction progress, optimize resource allocation, and forecast potential risks [6]. Through predictive analytics, AI helps minimize construction waste, reduce the likelihood of costly errors, and promote more efficient use of materials, key principles aligned with the circular economy. The integration of these digital technologies introduces a new level of intelligence across construction workflows, merging immersive interaction with data-driven insights.

Despite the clear potential of VR, AR, and AI, current research remains fragmented. Many studies focus on isolated applications, such as AI for defect detection, VR for training, or AR for site visualisation, without exploring how these technologies can work together to create a holistic digital ecosystem that improves sustainability and operational performance [7]. Moreover, the practical implementation of such integrated systems presents conceptual, technical, and organisational barriers that require deeper theoretical examination.

This paper aims to provide a thorough theoretical analysis of how integrating AI, VR, and AR can enhance construction processes. The study examines their combined potential to improve visualisation, automate quality control, strengthen decision-making, and support more efficient and sustainable resource use, in line with the principles of the circular economy. This article also outlines future research directions and proposes a conceptual framework for integrating these technologies into construction environments, providing a foundation for academics and practitioners seeking to adopt advanced digital solutions.

This study is guided by the following research question: how can the integrated application of VR, AR, and AI transform construction workflows to support resource efficiency, quality control, and the transition to circular economy principles across the building lifecycle? To address this question, the paper conducts a systematic theoretical analysis of the technical capabilities and synergies of each technology, framing their combined potential within a conceptual integration model that spans design, construction, quality assurance, and post-construction maintenance. Within this scope, "resource prediction" refers specifically to the anticipation of material quantities, labour needs, and equipment utilisation based on three primary input streams: BIM-derived geometric and semantic data; historical project records encompassing productivity rates and waste generation logs; and real-time site data captured through IoT sensors, drones, and photogrammetric systems. The prediction time horizon ranges from short-term operational decisions (daily to weekly scheduling) to medium-term project planning (monthly milestones), with accuracy evaluated through standard regression metrics such as Mean Absolute Percentage Error (MAPE) and Root Mean Squared Error (RMSE), or classification metrics such as F1-score for defect detection applications.

Compared with prior reviews that address VR [1], AR [19,20], or AI [12] in isolation, the specific scientific contribution of this paper lies in its unified theoretical framing of these three technologies as an interdependent ecosystem. Unlike earlier integration studies that tend to focus on specific project phases or individual application domains, this work articulates a lifecycle-spanning conceptual framework that connects design, construction execution, quality assurance, and post-construction maintenance, and explicitly links the technological integration to circular economy performance indicators. This positions the present study as a synthesis contribution that bridges the gap between technology-specific literature and systems-level sustainability objectives in the construction sector.

2 Background: digital transformation in construction

Over the past three decades, the digital transformation of the construction industry has gradually unfolded, fundamentally altering how projects are conceptualized, designed, coordinated, and executed. Traditionally, the construction sector has been marked by fragmented workflows, low levels of automation, and a heavy reliance on manual documentation systems, all of which have contributed to inefficiencies, rework, and communication breakdowns [6]. As global challenges such as climate change, urbanization, workforce shortages, and resource scarcity become increasingly pressing, the limitations of conventional practices have come to the forefront. This has generated significant momentum toward the adoption of digital technologies that foster more innovative, safer, and more sustainable project environments [8].

2.1 From manual workflows to digital foundations

Initially, construction practices relied heavily on manual drafting, physical models, and paper-based documentation. This dependency led to frequent communication gaps, inconsistencies in project documentation, and a heightened risk of error propagation. The introduction of computer-aided design (CAD) in the late 20th century marked a significant shift towards digital workflows, facilitating faster drafting and enhancing accuracy [9]. However, CAD models largely remained geometric representations that lacked embedded information and coordination capabilities.

The emergence of BIM marked a second, more transformative wave of digitalization. BIM integrates geometrical, structural, and operational data into a cohesive model, serving as a shared knowledge resource accessible throughout the project's lifecycle [2]. This advancement improved interdisciplinary coordination, clash detection, cost estimation, and scheduling. Nevertheless, BIM models tend to be static, offering limited real-time interaction and predictive capabilities.

2.2 Rise of immersive technologies

To overcome the limitations of static digital modeling, immersive technologies, especially VR and AR, have emerged as powerful tools for enhancing on-site design comprehension and accuracy. VR allows stakeholders to immerse themselves and navigate in digital models, providing a deeper understanding of spatial relationships, design intent, and potential safety risks [1]. This capability fosters improved interdisciplinary coordination and significantly reduces design-related errors, particularly in complex projects such as hospitals, industrial facilities, and transportation infrastructure.

Conversely, AR offers dynamic overlays of digital content onto the physical condition of a job site. Unlike VR, which creates an entirely virtual environment, AR enriches the real world, enabling workers, inspectors, and engineers to visualize and dialogue with BIM elements directly on site. This facilitates tasks such as installation alignment, layout verification, clash detection, quality assurance (QA/QC) [10] and expands the understanding of physical reality. AR technologies, accessible on tablets, smartphones, or wearable headsets like the Microsoft HoloLens, represent a significant advancement in bridging the gap between digital project information and physical construction activities.

2.3 Emergence of data-driven intelligence

While VR and AR enhance visualisation, they do not inherently provide predictive or analytical capabilities. The next phase of digital transformation in construction is characterised by the integration of AI, which automates, enables learning, and supports data-driven decision-making across construction workflows [11].

Machine learning algorithms can analyse historical and real-time data to forecast schedule delays, optimise material quantities, and identify patterns that indicate safety risks or structural anomalies. Additionally, computer vision systems can automatically detect defects, such as cracks, misalignments, corrosion, or missing components, in images, videos, or drone-captured data [12]. Advanced deep learning architectures enable precise segmentation of point clouds, thereby improving the accuracy of digital twins and supporting as-built verification.

AI effectively shifts the construction industry from reactive to predictive and proactive methodologies. When paired with VR and AR, AI serves as the analytical engine that enriches immersive data visualization, allowing construction teams to access predictions, alerts, and recommendations directly within simulated or physical environments [13].

3 Technologies in detail

The integration of VR, AR, and AI represents one of the most significant advancements in the construction industry's digital transformation. Although these technologies are often examined independently, their combined potential can be fully understood only by examining their technical foundations, operational capabilities, and inherent limitations. VR provides fully immersive and interactive digital synthetic environments that enhance spatial comprehension, facilitate design validation, and allow teams to simulate construction sequences or safety scenarios before project execution [14]. AR extends these capabilities into the physical jobsite by overlaying digital information, such as BIM components, annotations, or quality-control indicators, onto real-world environments, supporting precision during installation, onsite verification, and real-time problem-solving [7]. AI, meanwhile, introduces powerful predictive and analytical capabilities through computer vision, machine learning, and data-driven optimization, enabling automated defect detection, progress monitoring, and resource forecasting. Taken together, these technologies form a complementary ecosystem in which immersive visualization enhances the interpretation of AI insights, and AI algorithms, in turn, strengthen the performance of VR and AR applications through real-time analytics and intelligent feedback loops [13].

Understanding the evolution, applications, and constraints of each technology is therefore essential for evaluating their synergistic impact on construction workflows. Over the past decade, VR and AR tools have advanced significantly in terms of hardware performance, rendering capabilities, and device portability, making immersive environments more accessible to design teams and field personnel alike [14]. Similarly, AI techniques, particularly deep learning, computer vision, and natural language processing, have matured to process increasingly complex datasets captured through drones, mobile devices, LiDAR, and IoT sensors. However, challenges remain, including interoperability gaps across platforms, computational requirements, limitations in data quality, and workforce training needs. By examining the strengths and weaknesses of VR, AR, and AI collectively, this section lays the groundwork for a holistic understanding of how these technologies can be integrated into a unified digital framework capable of transforming construction planning, execution, and lifecycle management.

3.1 Virtual Reality (VR)

VR is a computer-generated, three-dimensional environment that immerses users in a fully digital world, allowing them to perceive, navigate, and interact with virtual elements as if they were physically present in the simulated space [6]. Unlike traditional visualization methods that rely on flat, two-dimensional screens, VR creates a sense of presence, often described as “being inside” the digital environment, by using head-mounted displays (HMDs), motion-tracking systems, and stereoscopic rendering techniques [15]. These systems track the user’s head and body position and orientation in real time, adjusting visual and auditory stimuli accordingly to create a natural and intuitive experience [1]. VR can also be enhanced in full-body environments so-called CAVE (Cave Automatic Virtual Environments) using audiovisual content, projections, voice recognition and lightning.

VR environments are designed to replicate real-world conditions or generate simulated scenarios that may not yet exist, making them particularly valuable for construction applications [16]. Through VR, users can explore full-scale digital models, assess spatial layouts, examine constructability, and identify potential design conflicts long before any physical work begins [1]. The ability to move freely within the virtual environment enhances depth perception and spatial understanding, helping stakeholders visualize geometric relationships, structural configurations, and architectural features with far greater clarity than traditional drawings or flat-screen 3D models. The modularity of VR technologies expands the range of human visual perception with x-ray, wireframe, thermic and conflict-based scenarios.

Moreover, VR supports interactive behaviors within these environments. Users can manipulate objects, test different design alternatives, simulate construction sequences, rehearse safety procedures, or evaluate logistical constraints [14]. Advanced VR systems integrate haptic feedback, providing tactile sensations that further enhance realism and user engagement [1]. By creating a high-fidelity representation of the built environment, VR enables more informed decision-making, improves interdisciplinary coordination, and reduces the cognitive effort required to interpret complex technical information.

This combination of immersion, interaction, and realism makes VR one of the most transformative technologies in the construction industry, capable of bridging the gap between digital design and physical execution [1].

3.1.1 Types of VR in construction

VR systems employed in construction can be categorized into three primary formats:

- **Immersive VR** [17]: Utilizes HMDs such as Oculus Quest, HTC Vive, or Meta XR, allowing stakeholders to virtually "walk through" a building before construction begins. Immersive VR is beneficial for design validation, safety training, and stakeholder engagement.
- **Semi-immersive VR** [17]**:** Involves large projection screens or CAVE systems, providing partial immersion. These setups support collaborative design review among multiple users.
- **Non-immersive VR (desktop VR)** [17]**:** Relies on traditional monitors and offers simpler navigation through 3D environments. Though less immersive, it is more accessible and frequently used for preliminary design analysis.

3.1.2 Applications of VR in construction

VR enables a wide range of applications across the construction lifecycle by providing immersive and interactive digital environments that support planning, training, decision-making, and communication [17]. One of the most prominent uses of VR lies in design and planning optimisation, where immersive visualisation allows teams to evaluate spatial layouts, circulation patterns, sightlines, and ergonomic considerations at early project stages. Unlike traditional 2D drawings or non-immersive 3D models, VR enables users to experience the space at full scale, walk through rooms and corridors, assess design alternatives, and identify potential conflicts related to geometry, accessibility, or human behaviour [18]. This capability not only improves design quality but also reduces the likelihood of costly modifications during construction.

VR also plays a critical role in safety training, an essential aspect of construction management due to the high-risk nature of many onsite activities. Through realistic simulations of hazardous scenarios, such as falls from heights, equipment collisions, unstable scaffolding, or confined-space risks, VR provides workers with controlled environments in which to practice appropriate responses without exposure to real danger [16]. Immersive safety training has been shown to improve risk perception, knowledge retention, and situational awareness, ultimately contributing to fewer accidents and safer job sites.

In addition, VR enhances construction sequencing and logistics planning by enabling teams to visualise the step-by-step progression of activities before work begins. Construction managers can simulate equipment movements, crane positioning, delivery routes, material staging areas, and temporary structures within the virtual environment [15]. These simulations enable stakeholders to identify spatial conflicts, optimise workflows, and evaluate alternative strategies to reduce bottlenecks. By visualising construction processes in 4D, integrating time as a simulation component, teams gain a clearer understanding of sequencing dependencies and potential impacts on schedule and cost.

Another key application of VR is stakeholder communication and engagement, particularly with clients, facility managers, or community members who may not possess technical backgrounds. VR simplifies the interpretation of complex design information by enabling non-experts to understand architectural intent, structural features, interior layouts, material options and the effect of natural light in an intuitive, immersive way [16]. This capability reduces misunderstandings, facilitates more informed decision-making, and strengthens collaboration between project teams and stakeholders. VR also supports remote participation, enabling geographically dispersed individuals to join virtual walkthroughs, evaluate design proposals, and provide real-time feedback.

VR environments can visualise "buildings as material banks," showing material provenance, bill of quantities, and disassembly procedures to support future reuse and recycling. Material and components can be viewed and advertised digitally, thereby implementing a digital market of used construction elements. A number of hidden features can be added to the VR model and be triggered during navigation to provide information about hidden or inaccessible elements. This is an important feature of VR when designing for assembly and disassembly, helping to program sequences of separation and calculate the potential of building circularity [19].

Overall, VR serves as a powerful tool that enhances design quality, improves planning accuracy, strengthens safety culture, and fosters collaborative decision-making. Its ability to merge visualisation with simulation provides a foundation for more efficient, transparent, and informed construction processes.

3.1.3 Limitations and Challenges of VR

Despite its transformative potential, VR adoption in the construction industry faces several technical, organisational, and practical challenges that limit its large-scale implementation. One of the primary constraints relates to hardware and computational requirements. High-fidelity VR environments demand significant processing power to render large BIM models, complex geometries, and realistic lighting conditions at interactive frame rates [15]. Many construction projects involve intricate structural components and high-resolution textures that can overload standard VR systems, causing latency, reduced image quality, or motion sickness among users [16]. These performance constraints require advanced graphics cards, powerful processors, and optimised modelling practices, which can increase implementation costs and raise the barriers to widespread adoption.

Another challenge concerns integrating BIM models into VR environments. Although BIM provides detailed 3D representations of buildings, these models are often too heavy, fragmented, or semantically inconsistent to be used directly in VR applications [16]. Converting BIM data into VR-ready formats may require extensive preprocessing, such as model simplification, mesh optimization, or removal of non-essential elements [15]. These additional steps increase preparation time and demand specialized digital skills. Furthermore, inconsistencies between BIM authoring platforms and VR engines can create interoperability issues, hindering seamless information transfer between tools.

User-related limitations also play a significant role. Many construction professionals may experience cyber-sickness, characterized by dizziness or nausea resulting from visual-vestibular conflict when navigating virtual spaces [16]. Prolonged VR exposure can lead to fatigue, discomfort, and reduced productivity, which may discourage continued use. Additionally, operating VR systems requires a learning curve; not all workers or stakeholders possess the digital literacy necessary to interact effectively with immersive environments [15]. Organizations must therefore invest in training programs and digital upskilling to ensure effective adoption of tools.

Practical constraints at the jobsite level also hinder VR implementation. VR requires controlled environments where users can move safely without obstacles, which is difficult to ensure on active construction sites, where equipment, uneven surfaces, and safety risks abound [7]. This limits VR's use primarily to off-site design review, training facilities, or dedicated virtual coordination rooms [16]. While mobile VR devices exist, they often lack the fidelity, tracking accuracy, or robustness needed for construction-level applications.

Cost remains another significant barrier. High-quality VR headsets, motion trackers, and powerful computing hardware can be expensive, especially for small and medium-sized firms with limited budgets. Although technology prices are gradually decreasing, additional costs related to software licenses, training, and digital content creation still represent a substantial investment [16]. Without clear cost–benefit benchmarks or industry-wide guidelines, many companies struggle to justify VR adoption.

Finally, limited standardisation poses a strategic challenge. There is currently no universal framework for integrating VR with BIM, scheduling tools, or project management platforms [16]. As a result, VR solutions remain fragmented, with inconsistent data structures, varying levels of detail, and differing visualisation standards across projects [15]. This lack of standardisation reduces interoperability and complicates collaborative workflows.

3.2 Augmented Reality (AR)

AR enhances the physical environment by overlaying digital information, such as BIM components, annotations, construction tolerances, safety indicators, and geometric guidelines, directly into the user’s field of view [20]. Unlike VR, which immerses users in a fully synthetic digital world, AR preserves the physical surroundings and enriches them with contextual digital content. This mixed visualisation allows users to simultaneously perceive actual construction conditions and the corresponding digital elements that guide, verify, or complement onsite activities [21].

AR systems operate by using devices such as tablets, smartphones, smart glasses, or optical see-through headsets (e.g., Microsoft HoloLens) equipped with cameras, depth sensors, and spatial mapping algorithms. These devices capture the physical environment in real time and superimpose virtual objects with precise geometric alignment, a process known as spatial registration [22]. Through advanced computer vision techniques, AR platforms detect surfaces, recognise patterns, and anchor digital elements to specific locations, ensuring that BIM-based overlays match the dimensions and orientation of physical components with high accuracy.

In the construction context, AR’s primary value lies in its ability to bring design intent directly to the jobsite [23]. Workers can visualise structural elements, installation guidelines, reinforcement layouts, or alignment references directly on the actual building components, drastically reducing interpretation errors that often occur when relying solely on 2D drawings or static models. For instance, AR can highlight the exact location of conduits behind walls, indicate the correct position of steel reinforcements, or show the intended geometry of complex formwork systems [20]. This real-time guidance improves precision, accelerates installation processes, and minimises costly rework.

Furthermore, AR supports advanced quality assurance and quality control (QA/QC) workflows by enabling inspectors to compare as-built conditions with BIM models in real time. Deviations, omissions, or misalignments can be identified visually on-site, reducing the need for manual measurements or prolonged inspection procedures [21]. AR also facilitates remote collaboration by enabling off-site experts to view the jobsite from the perspective of on-site workers, provide instructions, and annotate live video feeds, improving communication and reducing delays.

3.2.1 AR technologies and devices

AR technologies rely on a variety of hardware platforms that enable users to visualize digital information superimposed onto real-world environments [20]. These devices differ in terms of interface, mobility, precision, and immersive capability, allowing AR applications to be tailored to the diverse needs of construction sites. The most accessible entry point to AR is through smartphones and tablets, which utilize built-in cameras, gyroscopes, accelerometers, and depth sensors to detect surfaces and anchor virtual elements [23]. Their portability and low cost make them particularly suitable for rapid on-site checks, basic alignment verification, and the visualization of BIM elements directly on the device’s screen [20]. Although these devices do not provide whole hands-free interaction, their widespread availability makes them a practical starting point for AR adoption in field operations.

Optical see-through headsets, such as the Microsoft HoloLens and Magic Leap, enable more advanced AR experiences. These devices use transparent lenses that overlay holographic content onto the user’s natural field of view, enabling hands-free interaction with digital models while allowing complete awareness of the surrounding environment [20]. By integrating depth sensors, spatial-mapping algorithms, and gesture-recognition systems, these headsets create highly precise, stable overlays that are essential for tasks requiring acceptable positional accuracy, such as verifying as-built conditions, inspecting tolerances, or guiding workers during complex installations [21]. Their ability to process BIM data, display annotations, and support collaborative holographic reviews makes them particularly valuable for coordination meetings and advanced QA/QC workflows [22].

A third category consists of wearables and smart glasses, which offer lighter, more compact devices designed for continuous on-site use. These systems, such as Vuzix and RealWear headsets, typically prioritise durability, voice control, and real-time access to information over fully immersive holographic visualisation [20]. Although their AR capabilities are comparatively limited, they excel in environments where mobility, safety, and operational practicality are essential. Workers can receive remote expert assistance, capture field data, and access digital instructions without interrupting their workflows [21]. These devices enhance documentation efficiency, support field reporting, and enable rapid inspection cycles.

Together, these AR devices form a spectrum of technological solutions, ranging from entry-level visualisation tools to advanced holographic computing systems [23]. Their selection depends on the complexity of construction tasks, the precision required, environmental conditions, and the organisation’s digital maturity [20]. As AR hardware continues to evolve, becoming lighter, more accurate, and more affordable, its integration into everyday construction activities is expected to become increasingly seamless and impactful.

3.2.2 Limitations and challenges of AR

Despite its significant potential to enhance onsite accuracy, coordination, and decision-making, AR faces several technical, practical, and organisational challenges that limit its widespread adoption in the construction industry [21]. One of the most prominent limitations relates to spatial registration accuracy, which refers to the ability of AR systems to align digital BIM elements with the real-world environment correctly [23]. Construction sites are dynamic, cluttered, and often subject to irregular lighting, dust, vibrations, and occlusions. These factors interfere with computer vision algorithms and depth-sensing capabilities, leading to digital overlays drifting or misaligning. Even minor registration errors can compromise measurement accuracy, mislead field workers, and diminish trust in the technology.

Another major challenge involves environmental variability. AR devices rely heavily on sensors, cameras, and surface recognition algorithms that are sensitive to changes in natural light, weather conditions, and material reflectivity [23]. Outdoor construction environments, with strong sunlight, shadows, glare, and uneven surfaces, often pose difficulties for AR tracking systems. Additionally, indoor environments may contain repetitive geometric patterns or insufficient visual features, which can hinder markerless AR recognition [22]. These environmental constraints limit the reliability and consistency of AR for precision-dependent tasks, such as rebar placement, installation alignment, or inspection verification.

The hardware limitations of AR devices also present significant obstacles. Although smartphones and tablets are widely accessible, their AR capabilities are constrained by limited battery life, processing power, and the need for handheld operation, which reduces usability in environments that require both hands [20]. More advanced see-through headsets, such as the Microsoft HoloLens, offer improved functionality but remain bulky, impact-sensitive, and less suitable for harsh job-site conditions. These devices can be uncomfortable during prolonged use and may require protective accessories that further restrict movement or visibility [21]. The cost of high-end AR hardware also remains a barrier for many construction firms, tiny and medium-sized enterprises with limited digital budgets.

Interoperability issues further restrict AR adoption. Many AR applications depend on proprietary file formats and do not seamlessly integrate with BIM authoring tools or project management software [22]. Model conversion, simplification, or segmentation is often necessary to prepare BIM content for AR visualization, which increases processing time and demands specialized technical skills [23]. Without standardized workflows or universal data formats, AR remains isolated within digital ecosystems, reducing its effectiveness in multi-stakeholder environments.

From an organizational perspective, the digital skills gap presents an additional challenge. Construction personnel may lack familiarity with AR devices, leading to low adoption rates, user resistance, or inconsistent implementation [21]. AR requires training not only in device operation but also in interpreting digital overlays, understanding tolerances, and integrating AR insights into daily construction workflows. Without strong leadership support and structured training programs, organizations may struggle to realize the full benefits of AR.

Safety and ergonomic concerns also warrant consideration. Wearing AR glasses on active construction sites can obstruct peripheral vision or distract users from physical hazards. Prolonged use may lead to eye strain, fatigue, or discomfort, reducing operational efficiency [23]. Ensuring that AR enhances safety rather than compromises it requires careful workflow integration, device design improvements, and clear usage protocols [20].

3.3 Artificial Intelligence (AI)

AI refers to the development of computational systems capable of performing tasks that traditionally require human intelligence, such as learning from experience, recognising patterns, interpreting data, predicting outcomes, and making decisions [14]. Unlike traditional rule-based software, which operates strictly within pre-programmed instructions, AI systems adapt their behaviour based on the information they process. This capacity for autonomous learning, especially when combined with advanced data inputs from sensors, images, and BIM models, has positioned AI as a transformative force in the construction industry [3].

In this study, AI-based resource prediction encompasses forecasting material quantities, labour requirements, and equipment utilisation throughout the construction lifecycle. This process draws on three primary input data streams: (i) BIM-derived geometric and semantic data, including element quantities, material specifications, and spatial configurations; (ii) historical project records encompassing productivity rates, waste generation logs, and procurement datasets; and (iii) real-time site data captured through IoT sensors, drones, and photogrammetric systems. The prediction time horizon spans from short-term operational decisions, such as daily and weekly scheduling, to medium-term project planning at the monthly milestone level. Model accuracy is typically assessed using regression-based metrics, including Mean Absolute Percentage Error (MAPE) and Root Mean Squared Error (RMSE), while classification tasks, such as defect detection, are evaluated using F1-score and detection accuracy. These parameters define the operational scope within which AI contributes to resource-efficiency and circular-economy objectives in the integrated VR-AR-AI framework proposed in this study.

At its core, AI encompasses several subfields, each with unique capabilities that support different aspects of construction workflows. Machine Learning (ML) enables algorithms to identify statistical patterns in historical or real-time data, allowing systems to forecast potential delays, material needs, or safety risks. Deep Learning (DL), a subset of ML, uses neural networks with multiple layers to analyze complex data inputs such as images, videos, LiDAR point clouds, and sensor measurements, making it particularly useful for defect detection, progress tracking, and automated classification of construction components [7]. Computer Vision, another AI-affected domain, focuses on enabling machines to "see" and interpret visual information, allowing construction systems to evaluate artistry, detect anomalies, and monitor physical activities with unprecedented precision.

In the construction context, AI's main contribution lies in its ability to convert raw, fragmented, and unstructured data into meaningful insights. Construction projects generate enormous amounts of information through BIM models, site photographs, drone captures, inspection reports, IoT sensors, and daily logs [24]. AI algorithms process this data to identify correlations, detect outliers, and generate predictions that support evidence-based decision-making. For example, computer vision models powered by AI can automatically identify cracks, misalignments, or missing reinforcements from site images, reducing the need for manual inspections [18]. Predictive algorithms can estimate project delays based on early productivity trends or optimise material ordering to minimise waste and reduce environmental impact.

Moreover, AI supports the shift toward proactive construction management. Instead of responding to issues after they arise, predictive analytics allow teams to anticipate potential failures, safety hazards, or resource shortages before they disrupt progress [6]. This early-warning capability aligns with broader sustainability and circular economy goals by minimising rework, reducing waste, and extending the lifespan of structures through timely maintenance interventions.

Despite its potential, AI implementation faces challenges. High-quality datasets are necessary to train robust models, yet construction environments are highly variable and often lack standardised data collection protocols. Additionally, the opacity of some AI models, known as the "black-box" problem, raises concerns about transparency and trust among practitioners. Overcoming these barriers requires improved data governance, open datasets, explainable AI techniques, and training programs to enhance digital literacy among construction professionals.

3.3.1 Core AI techniques relevant to construction

AI encompasses a wide range of computational techniques designed to replicate human cognitive functions such as learning, perception, pattern recognition, and decision-making. In the construction industry, where large volumes of heterogeneous data are generated daily, AI plays a pivotal role in automating processes, improving prediction accuracy, and enabling data-driven insights. Several core AI subfields have emerged as particularly relevant to construction applications due to their ability to process complex visual, numerical, and textual data.

One of the most foundational techniques is ML, which enables algorithms to identify patterns and relationships within structured or unstructured datasets. ML models learn from historical project records, sensor data, and site observations to forecast outcomes such as project delays, cost overruns, productivity fluctuations, or material demand [7]. Common ML approaches include regression models, decision trees, random forests, and clustering techniques, each offering unique capabilities for classification, prediction, or anomaly detection. ML provides the analytical basis for developing intelligent systems that support proactive planning and real-time optimisation in construction workflows [25].

A more advanced subset of ML is DL, which leverages multi-layered neural networks to process high-dimensional data. DL has gained significant traction in construction due to its superior performance in analysing images, videos, and 3D point clouds, data types increasingly common in drone inspections, laser scanning, and photogrammetry-based workflows [7]. Convolutional Neural Networks (CNNs), for example, excel in tasks such as defect detection, reinforcement identification, segmentation of structural elements, and recognition of worker behaviours. Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks are used for temporal predictions, including forecasting schedule deviations or analysing equipment usage patterns.

Another key AI-affected domain relevant to construction is Computer Vision, which equips machines with the ability to "see" and interpret visual information captured from cameras or sensors. Computer vision techniques enable systems to automatically detect cracks, spalling, misalignment, missing components, improper installation, or unsafe on-site behavior [7]. These methods enable automated QA/QC, remote inspection workflows, progress monitoring through photographic comparison, and integration with AR overlays to highlight deviations in real time. Computer vision underpins many emerging digital twin platforms, where as-built conditions are continuously compared with BIM models.

Beyond visual data, Natural Language Processing (NLP) has emerged as a valuable AI technique for managing the vast amount of textual and audible information generated throughout construction projects. NLP algorithms can extract insights from daily reports, specifications, emails, change orders, and safety documentation [25]. They can identify recurring issues, automate documentation, classify safety incidents, or detect contractual risks. Contributions include translating audio information, supporting business meetings and transcribing verbal interactions. NLP also supports voice-controlled interfaces in AR/VR systems, enhancing usability in hands-busy environments.

Complementing these techniques, Reinforcement Learning (RL) is increasingly used in construction automation and robotics, where algorithms learn optimal sequences of actions through trial-and-error interactions with their environment [7]. RL enables applications such as autonomous equipment navigation, crane path optimization, and robotic component assembly. Although still emerging in construction, RL holds significant potential for advancing automation in tasks that involve dynamic decision-making under uncertainty.

Finally, optimization and heuristic algorithms, such as genetic algorithms, swarm intelligence, and mixed-integer programming, play an important role in resource allocation, scheduling, structural design optimization, and energy performance assessments [7]. These methods enable construction teams to rapidly explore multiple configurations and identify optimal solutions based on specific performance criteria.

Collectively, these AI techniques form a robust computational foundation capable of transforming construction processes through automation, prediction, and intelligent decision support [24]. When integrated with immersive technologies such as VR and AR, AI capabilities are amplified, enabling real-time insights to be visualized within intuitive environments and directly applied to on-site workflows [25]. This synergy is essential for advancing the construction industry toward a more efficient, resilient, and sustainable paradigm.

3.3.2 Limitations and challenges of AI

Although AI has demonstrated remarkable potential to transform construction practices through automation, prediction, and advanced data analysis, its widespread adoption remains constrained by several key limitations. These challenges span technical, organizational, ethical, and economic domains, illustrating the need for a more mature digital ecosystem before AI can be fully embedded within construction workflows [24].

A primary challenge involves the scarcity and inconsistency of high-quality data, which are essential for training reliable AI models. Construction environments are highly variable, presenting fluctuating lighting, irregular geometries, occlusions, dirt, dust, and rapidly changing site conditions. As a result, images and sensor data captured onsite often contain distortions, noise, or incomplete information, which can negatively affect the performance of computer vision and deep learning systems [7]. Moreover, the construction sector lacks standardized data collection protocols, leading to datasets that may differ significantly from one project to another in terms of format, labeling, structure, and content. This inconsistency limits the generalizability of AI models and increases the risk of inaccurate predictions or false detections [25].

Another critical limitation concerns the computational demands of AI technologies, particularly deep learning. Training and deploying large neural networks require significant processing power, high-performance GPUs, and continuous access to cloud computing platforms. Many construction firms, especially small and medium-sized enterprises, lack the infrastructure or financial resources to support such computational requirements [25]. Even when cloud solutions are available, issues such as latency, connectivity, and data upload restrictions on remote job sites can hinder AI performance, disrupt workflows, and reduce system reliability.

AI adoption also faces challenges associated with interpretability and transparency, often referred to as the "black-box problem." Many advanced AI models, particularly deep neural networks, generate predictions without providing clear explanations of how they were derived [25].This lack of interpretability creates hesitation among engineers, inspectors, and project managers who must justify decisions in safety-critical environments [7]. Without transparent or explainable AI techniques, users may struggle to trust AI recommendations, particularly when errors could have serious safety or economic implications.

From an organizational perspective, the construction industry continues to exhibit a significant digital skills gap. Most AI systems require specialized knowledge in data analytics, programming, cloud platforms, and algorithm interpretation, skills that are not traditionally part of construction training [24]. Many professionals feel overwhelmed by the perceived complexity of AI tools, leading to reluctance or resistance to adoption [7]. This skills gap highlights the need for comprehensive digital training programs, new competency frameworks, and collaborative partnerships between academia, industry, and technology providers.

Another organisational challenge is integration with existing workflows. Construction processes are highly fragmented, involving numerous stakeholders, subcontractors, and suppliers who often use a wide range of software systems and documentation styles. AI tools frequently operate in isolation and struggle to integrate seamlessly with BIM platforms, scheduling systems, quality control procedures, and field documentation. Without interoperability standards and unified data environments, AI solutions risk underutilization or misalignment with project needs [25].

Economic barriers also play a significant role in slowing AI adoption. Developing customised AI models, acquiring high-quality sensors, maintaining cloud subscriptions, and hiring specialised personnel can involve substantial upfront investment [24]. Many firms lack clear frameworks for quantifying the return on investment, making it difficult to justify long-term AI integration. Additionally, the construction industry is traditionally risk-averse; companies may hesitate to adopt emerging technologies without proven, widely accepted benchmarks of performance and reliability.

Finally, AI raises important ethical and privacy concerns. Data collected through cameras, drones, and wearable sensors may capture identifiable information about workers, raising issues of surveillance, consent, and compliance with data ions [25]. AI-driven automation also prompts concerns about workforce displacement, equity, and the need to redefine roles and responsibilities across job categories. If not managed responsibly, AI adoption may lead to mistrust, resistance, or legal complications.

In summary, while AI holds enormous promise for enhancing efficiency, accuracy, and sustainability in construction, addressing these technical, organisational, economic, and ethical limitations is essential for realising its full potential [24]. Overcoming these challenges requires a combination of standardised data practices, transparent AI models, improved digital literacy, robust governance frameworks, and strategic investment in interoperable technologies [25]. Only with these foundational elements in place can AI evolve from isolated experimental applications into a central component of intelligent and integrated construction ecosystems.

4 Integration framework of VR, AR, and AI in construction

The successful adoption of VR, AR, and AI in construction requires a structured and progressive implementation strategy that aligns technological capabilities with organisational readiness, project requirements, and long-term digital transformation goals [24]. The following subsections outline key implementation dimensions, offering a holistic view of how the industry can gradually integrate these technologies into daily practice. Figure 1 illustrates the proposed multi-layer digital architecture that links the design, construction, quality control, and post-construction phases through a unified data ecosystem. BIM models, structured according to ISO 19650 and interoperable formats such as IFC and gbXML, are managed within a CDE and enriched with real-time and historical data sources. These inputs feed an AI engine combining machine learning, deep learning, computer vision, natural language processing, and reinforcement learning to enable predictive analytics and automated decision support. The outputs are operationalised through VR for immersive planning and coordination, and AR for on-site guidance, inspection, and maintenance. The framework establishes a continuous digital feedback loop in which field data and AI insights update BIM/CDE models, supporting improved accuracy, reduced rework, and enhanced lifecycle performance. The resulting system contributes to circular economy objectives, including reductions in material waste and emissions, improved resource efficiency, and extended service life. Interoperability standards and implementation constraints relevant to real-world construction contexts are also highlighted.

4.1 Establishing the digital foundation

A robust digital foundation is essential for the effective implementation of immersive and intelligent technologies in construction. These technologies rely on high-quality, well-structured, and consistently managed digital information. Without such a foundation, VR, AR, and AI workflows become disconnected, unreliable, and difficult to scale. Ensuring digital readiness begins with establishing standardised, interoperable, and well-governed data environments across the organisation [20].

One of the most important prerequisites is the adoption of reliable BIM practices with consistent modelling standards. BIM models serve as the central source of geometric and semantic information used by VR environments, AR overlays, and AI analysis pipelines [20]. Poorly structured

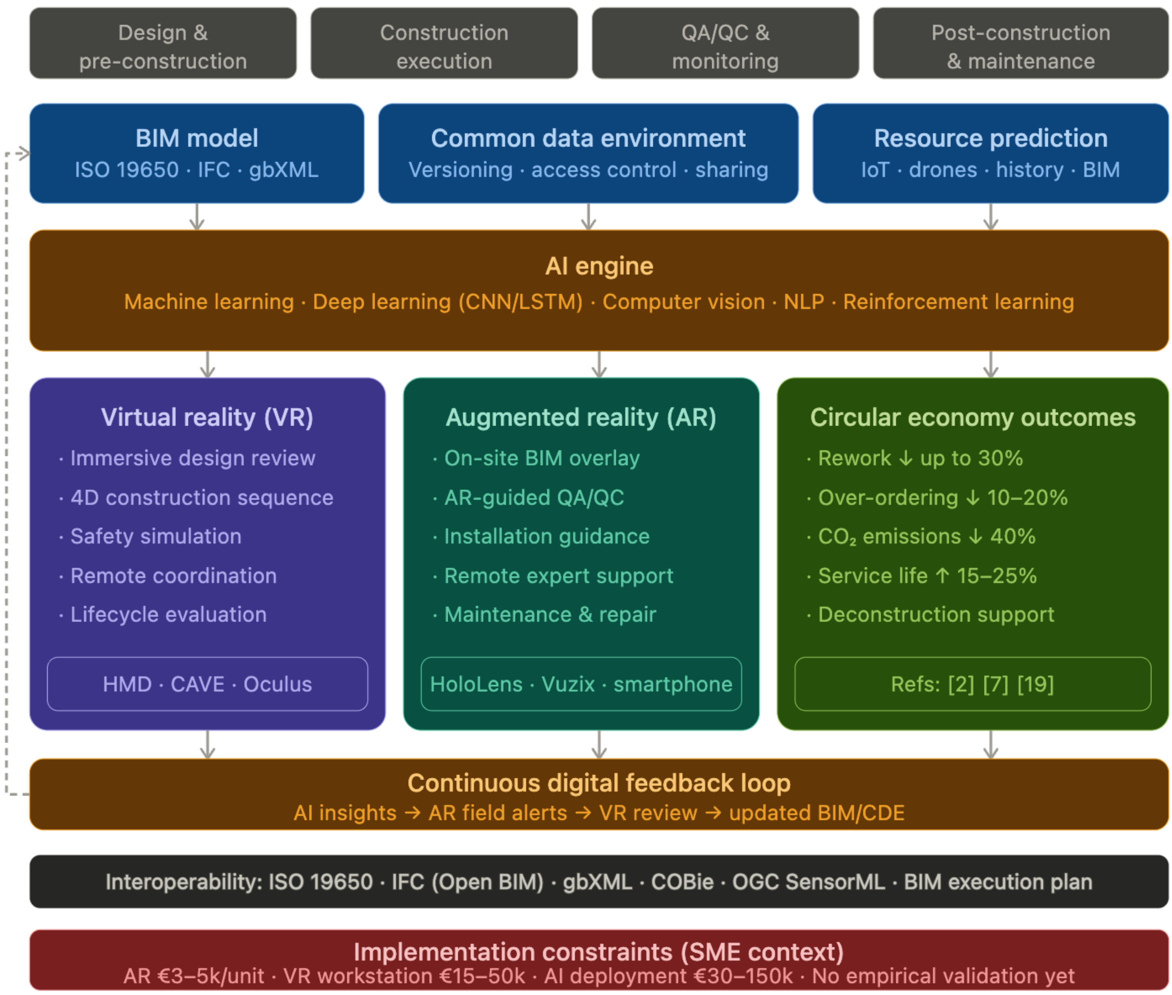

Figure 1. Proposed conceptual framework for the integrated deployment of VR, AR, and AI in circular and sustainable construction

BIM models, containing incorrect naming conventions, inconsistent levels of detail (LOD), or uncoordinated disciplines, create downstream problems that directly affect the accuracy of immersive visualisation and automated analytics. Establishing clear BIM execution plans (BEPs), defining model authorship responsibilities, and enforcing industry standards (such as ISO 19650) ensure that digital models remain coherent throughout the project lifecycle.

Equally important is the development of centralised data environments, such as Common Data Environments (CDEs). These platforms integrate project information from designers, contractors, suppliers, and clients into a single digital location. By maintaining documents, models, photos, drone captures, sensor datasets, and AI-generated reports in a structured environment, CDEs eliminate data fragmentation and ensure that all stakeholders have access to the most current information [24]. This level of centralisation is crucial for VR and AR tools, which require synchronised model updates, and for AI systems, which depend on consistent datasets for training and inference.

Another critical requirement is the establishment of interoperable file structures. Construction projects typically involve a variety of software platforms, BIM authoring tools, scheduling software, GIS, VR engines, AR viewers, drone capture systems, and AI algorithms. Without standardised file formats and workflows that enable smooth data exchange between these systems, integration becomes extremely inefficient [25]. Interoperability can be strengthened through open formats such as IFC and gbXML, as well as through clear protocols for exporting and converting models for VR/AR use. Seamless data exchange ensures that immersive and intelligent tools operate on accurate, up-to-date digital representations.

Finally, organisations must implement clear information management protocols that establish how digital data is created, stored, updated, and accessed. This includes naming conventions for BIM objects and files, version control systems to prevent outdated model use, update frequencies, validation procedures, and defined access rights [25]. These protocols prevent inconsistencies that can lead to errors in AR overlays, incorrect VR simulations, or inaccurate AI predictions. Proper information governance also reduces duplication, prevents data loss, and enhances traceability for quality assurance and decision-making [20].

Together, these foundational components create the digital consistency necessary for effective VR, AR, and AI integration [24]. When these elements are in place, immersive and intelligent technologies can operate smoothly, share information reliably, and support high-impact applications across construction workflows. Conversely, without this foundational structure, implementation efforts risk fragmentation, producing unreliable results, eroding user trust, and ultimately limiting the transformative potential of digital technologies in the construction industry.

4.2 Integration into design and pre-construction

The design and pre-construction phases provide the most structured and controlled environment for introducing immersive and intelligent technologies into construction workflows [7]. These early stages involve developing project concepts, coordinating multidisciplinary teams, planning logistics, and identifying potential risks, activities that benefit significantly from the combined use of VR, AR, and AI [25]. Integrating these technologies early in the project lifecycle establishes a solid digital foundation that enhances accuracy, reduces uncertainties, and improves decision-making long before physical work begins [17].

VR plays a central role during early design development by enabling stakeholders to immerse themselves in fully navigable digital models. Unlike traditional design review methods, which rely on drawings or flat-screen 3D visualisations, VR offers a full-scale representation of spaces, allowing designers and clients to assess spatial proportions, circulation paths, visibility, materiality, lighting, and user experience with greater clarity [20]. Through VR walkthroughs, teams can identify architectural inconsistencies, evaluate alternative layouts, and detect constructability issues that may not be apparent in conventional digital models [17]. This immersive environment enhances communication among architects, engineers, and clients, facilitating collaborative decision-making and early alignment on project goals.

AI enhances the design process by enabling automated and data-driven analysis of project models. Machine learning algorithms can evaluate design alternatives based on performance criteria such as energy consumption, structural efficiency, material quantities, or cost implications [25]. AI-based clash detection and rule-checking systems can assess BIM models for compliance with industry standards and project specifications, identifying potential conflicts earlier and with greater accuracy than manual reviews [7]. Predictive analytics provide insights on potential schedule risks, cost deviations, or constructability challenges, allowing project teams to make informed adjustments before committing to final designs [21].

AR complements VR and AI during pre-construction by providing real-world contextualization of digital components [25]. Early AR applications allow designers and engineers to visualise building elements within the actual site environment, enabling assessments of alignment, orientation, and interaction with surrounding structures [20]. For example, AR can be used during site walk-throughs to preview the placement of foundations, utilities, or site logistics zones, enabling more accurate planning and reducing the likelihood of conflicts during construction [21]. By bridging the digital and physical environments even before work begins, AR supports enhanced situational awareness and more precise early planning.

The integration of VR, AR, and AI also supports logistics planning and construction sequencing. VR-based 4D simulations allow teams to visualise step-by-step project progression, simulate crane operations, evaluate site access routes, and anticipate potential bottlenecks [17]. AI optimisation algorithms can analyse these simulations to propose more efficient sequencing strategies or resource allocations. AR can then be used during pre-construction meetings to overlay planned layouts on the physical site, validating the feasibility of chosen logistics strategies.

In addition, these technologies improve stakeholder communication by presenting complex design, safety, and planning information in intuitive and interactive formats. Clients, community representatives, and non-technical stakeholders can participate in VR walkthroughs or AR-enhanced site tours to gain a clear understanding of the project vision and potential impacts [20]. AI-generated insights, such as risk predictions or construction performance indicators, can be visualised in VR dashboards or AR overlays, making them easier to interpret and act upon [17].

4.3 Onsite Deployment During Construction

The construction phase represents the most dynamic and operationally complex stage of a project, where multiple teams, equipment, materials, and work sequences converge in a constantly changing environment. It is during this stage that errors, miscommunication, and inefficiencies are most likely to occur, making it an ideal context for the combined deployment of VR, AR, and AI [25]. When integrated effectively, these technologies help bridge the gap between digital planning and physical execution, enabling real-time guidance, automated quality control, and more informed decision-making on-site [20].

AR serves as the primary interface for on-site operations, enabling workers to visualise digital information directly in the physical environment. Using mobile devices or see-through headsets, field personnel can overlay BIM components onto actual construction elements, ensuring precise alignment for installations such as structural components, mechanical systems, reinforcement layouts, or architectural finishes [21]. This capability reduces ambiguity and improves the accuracy of field tasks that traditionally rely on paper drawings or manual measurements [7]. AR-based instructions can also guide workers step-by-step through complex assemblies, reducing dependency on supervision and minimising the likelihood of errors or omissions.

AI plays a complementary, often invisible role during on-site deployment by processing field data collected from cameras, drones, wearables, and sensors [25]. AI-powered computer vision models can analyse photos or videos of the site to automatically detect defects, missing components, dimensional deviations, or unsafe behaviours [21]. These systems can operate continuously, providing real-time alerts that allow supervisors to intervene before problems escalate. AI also supports progress monitoring by comparing as-built conditions with BIM models or schedule baselines, enabling automated quantification of work completion and early identification of delays [25].

VR remains relevant during construction as a tool for remote coordination, issue resolution, and stakeholder communication. By integrating drone scans, 3D photogrammetry, or 360° site images into immersive environments, VR enables project teams to conduct virtual site walks, assess construction progress, and collaboratively resolve issues without requiring physical presence [21]. This is particularly valuable for large infrastructure projects or projects with geographically distributed teams. VR can also facilitate daily or weekly coordination meetings by presenting site conditions in an intuitive, navigable format that enhances understanding and accelerates decision-making [17].

The integration of VR, AR, and AI during onsite deployment creates a continuous feedback loop between field conditions and digital systems. For example, AI can detect an alignment deviation in a structural element, which AR then displays to field inspectors as a visual highlight, allowing immediate correction [20]. The corrected condition can later be reviewed in VR by designers or managers to assess its implications for downstream tasks. This synergy enhances traceability, improves communication across disciplines, and reduces the time required to identify and resolve onsite issues.

However, successful implementation requires careful consideration of job-site conditions, device usability, and workflow integration. Construction sites are physically demanding environments where dust, vibration, weather conditions, and safety constraints can affect the performance and practicality of digital tools [7]. For this reason, AR hardware must be robust; AI algorithms must be adaptable to imperfect data; and VR coordination must complement, rather than replace, traditional site supervision [17]. Furthermore, digital workflows must be clearly defined so that field teams understand when and how to use each technology, ensuring compatibility with existing practices and minimising disruptions.

4.4 Quality assurance and quality control

Quality Assurance and Quality Control (QA/QC) are essential components of construction management, ensuring that projects meet design specifications, performance criteria, and safety requirements. Traditionally, QA/QC processes rely on manual inspections, paper-based checklists, and subjective assessments that can be time-consuming, inconsistent, and prone to human error [21]. The integration of AI, AR, and VR offers a transformative approach to improving the accuracy, consistency, and efficiency of quality control activities throughout the construction lifecycle [20].

AI plays a central role by automating defect detection and verifying compliance with digital models. By leveraging computer vision algorithms trained on large datasets of structural components, finishes, mechanical installations, and safety conditions, AI can analyse onsite images and videos to identify anomalies such as cracks, misalignments, missing reinforcements, surface defects, or nonconforming installations [25]. These systems can operate continuously via fixed cameras, drones, or wearable devices, providing real-time feedback that allows construction teams to address issues immediately [7]. Automated classification and segmentation models can also compare as-built conditions with BIM models, highlighting deviations that may compromise structural integrity or future performance.

AR enhances QA/QC processes by enabling inspectors to visualise digital information directly over the physical environment. Using mobile AR devices or see-through headsets, inspectors can overlay BIM elements, measurement guidelines, tolerance bands, or installation sequences onto the actual construction site. This allows precise verification of dimensions, alignment, and placement without relying solely on manual tools like tape measures or printed drawings [21]. AR supports immediate detection of differences between design intent and field execution; for example, highlighting a mispositioned cable tray or reinforcing bar in real time [20]. By providing intuitive visual cues, AR reduces ambiguity, accelerates inspections, and enhances communication between inspectors and field workers.

VR further supports QA/QC by enabling remote, interdisciplinary review. By converting site scans, such as 360° imagery, LiDAR point clouds, or photogrammetry models, into immersive VR environments, teams can conduct virtual inspections, review progress, and assess corrective actions without being physically present on site [7]. VR is particularly valuable for complex infrastructure projects, large-scale facilities, or worksites with restricted access [20]. Designers, engineers, and quality managers can jointly explore an immersive representation of the site, analyse issues detected by AI, and collaboratively validate proposed solutions. This virtual collaboration enhances coordination across disciplines and reduces scheduling delays for physical inspections.

When combined, VR, AR, and AI enable a comprehensive, end-to-end QA/QC system. AI-driven insights identify potential quality deficiencies; AR provides field teams with visual tools to verify and correct these deficiencies; and VR creates a platform for comprehensive review and documentation [17]. The synergy of these technologies ensures that corrective actions are taken promptly, deviations are minimised, and quality standards are maintained throughout the project lifecycle.

Additionally, digital QA/QC solutions generate detailed records, including annotated images, AI-generated reports, and AR-based verification logs. These digital records improve traceability, support compliance with regulatory standards, and serve as valuable documentation for facility handover and future maintenance [20]. Over time, accumulated QA/QC data can also be used to train improved AI models, creating a self-reinforcing cycle of continuous improvement [25]. Overall, integrating VR, AR, and AI into QA/QC processes enhances construction quality, reduces rework, minimises waste, and supports the long-term durability and performance of built assets [20]. By establishing a more precise, transparent, and efficient quality control framework, these technologies directly contribute to safer, more sustainable construction practices.

4.5 Post-construction and maintenance

Once construction is complete and the asset enters its operational phase, integrating VR, AR, and AI becomes essential to ensure long-term performance, durability, and sustainability. Post-construction activities, such as facility management, routine inspections, predictive maintenance, and lifecycle assessment, benefit significantly from digital technologies that enable continuous monitoring, intuitive visualisation, and data-driven decision-making [20]. These tools support the transition from reactive maintenance to proactive, predictive asset management aligned with circular economy principles and resilience objectives.

AI forms the analytical core of post-construction operations by processing data from sensors, inspections, historical records, and environmental monitoring systems [16]. Machine learning models can identify deterioration patterns, forecast component failures, and estimate remaining service life based on factors such as temperature, humidity, load variations, and material ageing [25]. AI-powered anomaly detection systems analyse sensor streams from structural health monitoring (SHM) devices, such as accelerometers, strain gauges, or corrosion sensors, to flag unusual behaviour, whether caused by fatigue, cracking, excessive deformation, or environmental stressors [7]. These predictive capabilities enable maintenance teams to intervene before failures occur, reducing downtime, minimising repair costs, and extending asset lifespan.

AR supports maintenance workflows by overlaying digital information directly onto the physical asset during inspections and repair tasks. Technicians can visualise internal elements, such as reinforcement layouts, embedded utilities, and previous repair histories, that are not visible to the naked eye [25]. By accessing BIM-linked AR overlays, maintenance personnel can see component specifications, deterioration predictions, and step-by-step repair instructions, reducing the likelihood of errors and accelerating interventions [20]. AR also facilitates remote support, allowing experts to guide onsite technicians through complex procedures via real-time annotations and visual cues [21]. This capability improves accuracy, reduces the need for specialist travel, and shortens response times.

VR remains valuable during the operational phase as a platform for training, planning, and scenario simulation. Facility managers can use immersive VR environments to understand the building's systems, rehearse maintenance procedures, and evaluate "what-if" scenarios related to natural hazards, system failures, or emergency responses [17]. For significant or critical infrastructure, VR enables safe exploration of hard-to-access areas, facilitating risk-free assessments and improving preparation for real-world interventions. VR also supports lifecycle evaluation by integrating updated digital models with operational data, enabling teams to visualize how the asset evolves [16].

Together, the integration of VR, AR, and AI creates a comprehensive digital ecosystem that enhances post-construction asset management [25]. AI provides continuous analytical insights; AR brings actionable, context-aware information directly to the jobsite; and VR supports immersive understanding and strategic planning [17]. This combination improves the quality and efficiency of maintenance activities, enhances safety, and reduces the environmental impact associated with premature deterioration and inefficient repair cycles.

Moreover, the digital records generated during post-construction, such as AI analysis reports, AR inspection logs, and VR-based maintenance simulations, form a valuable asset for future renovation, rehabilitation, or deconstruction efforts [21]. By maintaining a detailed, continuously updated digital history of the asset, organisations can adopt more circular, sustainable strategies, maximise material reuse, reduce waste, and support informed decision-making throughout the lifecycle.

4.6 Final remarks on implementation

The effective integration of VR, AR, and AI in construction requires not only technological readiness but also organisational alignment, structured planning, and a long-term commitment to digital transformation [20]. While each technology offers unique benefits when applied independently, their combined implementation yields a synergistic digital ecosystem that enhances accuracy, reduces waste, improves safety, and supports sustainable lifecycle management across the built environment.

A successful implementation strategy must be progressive, beginning with foundational digital practices, such as standardised BIM models, reliable data environments, and interoperable systems, and gradually evolving toward more advanced workflows that employ AI analytics, AR-guided execution, and VR-enabled coordination [25]. The transition from traditional methods to integrated digital processes cannot occur overnight; it requires iterative refinement, pilot programs, and deliberate capacity building to ensure that technologies are adapted to the specific needs and conditions of each project.

Moreover, implementation efforts must be supported by a clear vision of how these technologies align with organisational goals, project delivery strategies, and sustainability objectives [16]. VR, AR, and AI should not be treated as isolated "add-ons" but as interconnected tools that collectively enhance decision-making and operational performance [17]. Integrating them into routine planning meetings, onsite inspections, QA/QC workflows, and maintenance procedures ensures that their benefits become embedded in day-to-day operations.

Equally important is the development of a skilled workforce capable of leveraging digital tools effectively. Training programs, knowledge-sharing initiatives, and structured onboarding are essential to overcoming cultural resistance and building user confidence [25]. When construction personnel understand the value of immersive and intelligent technologies and are provided with intuitive workflows that complement their expertise, the adoption process becomes smoother and more impactful.

Finally, the successful implementation of VR, AR, and AI must be grounded in continuous evaluation and improvement [20]. As technologies evolve and new capabilities emerge, organizations should update their digital strategies, refine their workflows, and integrate new functionalities into existing systems [16]. This iterative process ensures that implementation remains aligned with industry advances and responsive to emerging challenges, including sustainability demands, regulatory changes, and evolving stakeholder expectations [21].

In summary, integrating VR, AR, and AI represents a strategic pathway toward a more efficient, accurate, and sustainable construction industry [25]. When supported by strong digital foundations, organisational readiness, and a structured implementation roadmap, these technologies can transform the entire lifecycle of construction projects, from design and planning to execution, quality control, and long-term maintenance, paving the way for next-generation digital construction ecosystems.

It is important to acknowledge the inherent limitations of this conceptual framework. The proposed integration model has not yet been empirically validated through controlled case studies; performance indicators referenced throughout this paper are drawn from individual pilot implementations in the literature rather than from systematic trials of the integrated system. Real-world adoption of the VR-AR-AI ecosystem also entails significant implementation costs that deserve explicit consideration. High-end AR headsets, such as the Microsoft HoloLens 2, range from approximately €3,000 to €5,000 per unit; professional VR workstation environments suitable for project coordination may require investments of €15,000–€50,000 per project node; and AI model development and deployment, including data infrastructure and cloud computing subscriptions, can demand between €30,000 and €150,000 in initial setup costs, depending on organisational digital maturity. Scalability is further constrained by connectivity requirements on remote or underground construction sites, interoperability gaps between proprietary software platforms, and the digital literacy levels typical of small and medium-sized enterprises (SMEs) in the construction sector. Future research should therefore prioritise empirical validation through structured pilot projects, standardised performance benchmarking across diverse project typologies, and the development of cost-benefit frameworks that support evidence-based adoption decisions at the firm level.

5 VR, AR, and AI for sustainability and the circular economy in construction

The integration of VR, AR, and AI offers a powerful pathway to align construction practices with sustainability objectives and circular economy principles [20]. As the built environment continues to account for a substantial share of global greenhouse gas emissions, resource consumption, and waste generation, digital technologies can play a crucial role in transforming traditional linear construction models, based on extraction, use, and disposal, into circular models that prioritise material efficiency, waste reduction, and lifecycle optimisation [25]. This section explores how each technology contributes to sustainability and how their combined application forms a robust framework capable of accelerating the transition toward circular construction systems.

To ground this analysis in measurable outcomes, it is instructive to reference quantitative benchmarks reported in the literature for individual technology applications. Studies integrating AI-driven quality control with AR-guided installation workflows have reported reductions in material rework of up to 30% [7], while predictive maintenance enabled by AI has been associated with extensions of asset service life of 15–25% compared with reactive maintenance strategies [7]. AR-assisted precision installation has been linked to reductions in material over-ordering of approximately 10–20%, directly contributing to lower construction waste levels [19]. Furthermore, BIM-integrated digital workflows have demonstrated CO_2 emission reductions of up to 40% per project lifecycle through optimized material procurement and reduced design iteration cycles [2]. While these figures derive from individual pilot implementations rather than from empirical validation of the present conceptual framework, they establish quantitative benchmarks against which future research should assess the integrated VR-AR-AI model proposed here. Recommended performance indicators for such validation include: percentage reduction in material waste and rework; improvement in material-use efficiency (kg of material per unit of completed work); reduction in CO_2-equivalent emissions per project; and extension of the mean service life of maintained assets.

5.1 Waste reduction through predictive insights and early error detection

One of the major contributors to waste in construction is rework, often caused by errors, misalignments, and inconsistencies between design and onsite execution. AI-powered computer vision enables early detection of these deviations by comparing progress photos, 3D scans, or video feeds against BIM models [21]. When deviations are identified promptly, corrective measures can be implemented before significant material or labour resources are wasted [25].

VR and AR enhance this process by providing intuitive visual interfaces that allow workers and engineers to inspect discrepancies more effectively [20]. AR overlays guide onsite teams with precise installation instructions, reducing mistakes that would otherwise lead to demolition or reinstallation. VR walkthroughs enable project teams to identify design inconsistencies before construction begins, preventing material waste later in the project [7]. Combined, these technologies support a predictive and preventive approach that drastically reduces rework, thereby decreasing energy use, emissions, and waste generation across the project lifecycle.

5.2 Resource efficiency and optimised material use

The efficient use of materials is a central pillar of circular construction. AI enhances resource optimisation through predictive analytics that estimate material consumption with greater accuracy [20]. Machine learning models can anticipate demand variations based on historical data, design complexity, and on-site productivity patterns, minimising over-ordering and unnecessary stockpiling.

AR facilitates precise installation processes, reducing the likelihood of errors that require additional materials. VR simulations also help project teams evaluate alternative materials, construction methods, and design configurations before execution, allowing for better-informed decisions that optimise resource use [16].

By integrating AI predictions with immersive VR/AR guidance, projects can maintain resource efficiency while improving overall productivity and reducing the environmental footprint associated with material production, transport, and waste [25].

5.3 Lifecycle optimisation and predictive maintenance

Circular economy principles emphasise extending the useful life of buildings and infrastructure through proactive maintenance, rehabilitation, and reuse strategies. The combination of VR, AR, and AI offers valuable support for lifecycle management [21].

AI-driven predictive maintenance algorithms analyse sensor data and inspection images to identify early signs of deterioration, such as cracks, corrosion, or excessive deformations [20]. These insights help asset managers schedule maintenance interventions before minor issues escalate into major failures, extending the service life of structures and reducing the need for resource-intensive repairs [7].

VR enables immersive evaluation of maintenance scenarios, facilitating safe exploration of confined or hazardous environments and allowing teams to plan interventions effectively [16]. AR provides a real-time overlay of structural conditions during inspections, guiding technicians to areas requiring immediate attention and enabling them to validate completed repairs with high precision [21]. These capabilities support a lifecycle-oriented approach that aligns with circular principles by reducing premature demolition, improving material reuse options, and maximizing the functional lifespan of assets.

5.4 Enhancing circular design and deconstruction practices

Circular construction requires not only efficient building processes but also designs that facilitate the reuse, remanufacture, or recycling of materials at the end of life [20]. VR plays a crucial role in evaluating design-for-disassembly strategies by enabling immersive testing of how components can be dismantled safely and efficiently.

AI can support deconstruction planning by identifying materials, estimating quantities, and predicting the recyclability or reuse potential of structural elements [17]. Meanwhile, AR allows onsite workers to visualise hidden components, such as reinforcement bars or embedded elements, reducing accidental damage during selective demolition [25]. Together, these tools support the transition from demolition-based practices to planned deconstruction, enabling the recovery of valuable materials and reducing landfill waste.

AR, when integrated with BIM, VR and AI, plays a critical role in operationalising material passports and enabling the implementation of buildings as material banks. By overlaying digital information onto physical assets, AR enables stakeholders to access detailed material data in situ, such as composition, disassembly potential, and reuse value. AR facilitates the visualisation of lifecycle information directly on building components, supporting more accurate identification, classification, and recovery of materials during maintenance and end-of-life phases [26]. This capability effectively bridges the gap between static material databases and real-world construction environments, transforming material passports into actionable tools. Consequently, AR enhances decision-making in selective deconstruction processes, reduces information loss across the lifecycle, and strengthens the traceability required for circular material flows.

6. Conclusions

The integration of VR, AR, and AI represents a transformative opportunity for the construction industry as it seeks to address persistent challenges in efficiency, sustainability, and digital modernisation. This paper provides a comprehensive theoretical analysis of how these three technologies, when strategically combined, can reshape construction workflows and support the transition toward circular, sustainable built environments.

The review of current technological capabilities demonstrates that VR enhances immersive visualisation and design comprehension, AR improves precision through real-time onsite guidance and augmented inspections, and AI introduces powerful analytical mechanisms that automate detection, optimise resource allocation, and support predictive decision-making. Individually, each technology offers valuable improvements; however, their true potential emerges when deployed as an integrated system. The conceptual framework proposed in this paper illustrates how data acquisition, intelligent analytics, and immersive interaction can be combined to create a continuous digital feedback loop that improves coordination, reduces rework, and supports lifecycle-oriented management.

The analysis also highlights how this integrated ecosystem aligns with circular economy principles by reducing waste, optimizing material use, extending the lifespan of assets through predictive maintenance, and enabling more efficient design and deconstruction practices. Despite its potential, the widespread adoption of VR, AR, and AI remains limited by several challenges, including interoperability constraints, computational demands, skill gaps, organizational resistance, and the high initial implementation costs [21]. Ethical considerations related to privacy, data governance, and workforce impacts also require careful attention. Addressing these barriers will require coordinated efforts from researchers, industry practitioners, policymakers, and technology developers.

Future directions identified in this study indicate that integrating immersive and intelligent technologies with digital twins, IoT sensing networks, and open data standards will be crucial to enabling fully intelligent and sustainable construction ecosystems. Continued research is necessary to improve robust AI models, generate standardized datasets, enhance the usability of immersive tools in real construction environments, and refine digital workflows that support circularity across the entire building lifecycle.

Overall, this work contributes to the growing body of knowledge on digital transformation in construction by articulating a unified theoretical perspective on how VR, AR, and AI can jointly support sustainable, efficient, and circular practices. The proposed framework serves as a foundation for future empirical studies and offers practical guidance for stakeholders seeking to implement advanced digital technologies in the construction sector.

Author Contributions

Conceptualisation, G.C.C.P., B.M.R. and L.B.; methodology, G.C.C.P.; software, G.C.C.P.; formal analysis, G.C.C.P.; investigation, G.C.C.P.; resources, and L.B.; writing—original draft preparation, G.C.C.P. and B.M.R. ; writing—review and editing, G.C.C.P., B.M.R. and L.B.; visualisation, G.C.C.P.; supervision, L.B; project administration, L.B.; funding acquisition, L.B. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding. However, the authors acknowledge the support of CYTED Network ECoEICo—Circular Economy as a Strategy for a More Sustainable Construction Industry and the COST Action CircularB—Implementation of Circular Economy in the Built Environment.

Acknowledgments

The authors of this article would like to thank the European Union and COST (European Cooperation in Science and Technology) for supporting the COST Action CircularB CA21103 www.circularb.eu.

Conflicts of Interest

The authors declare no conflicts of interest.

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