Extended Reality as a Catalyst for Circular Economy Transition in the Built Environment

Soman, R.K.; Nikolić, D.; Sanchez, B.

DOI
10.1007/978-3-031-39675-5_10

Publication date
2024

Document Version
Final published version

Published in
A Circular Built Environment in the Digital Age

Citation (APA)
Soman, R. K., Nikolić, D., & Sanchez, B. (2024). Extended Reality as a Catalyst for Circular Economy Transition in the Built Environment. In C. De Wolf, S. Çetin, & N. Bocken (Eds.), *A Circular Built Environment in the Digital Age* (pp. 171-193). (Circular Economy and Sustainability). Springer. https://doi.org/10.1007/978-3-031-39675-5_10

Chapter 10
Extended Reality as a Catalyst for Circular Economy Transition in the Built Environment

Ranjith K. Soman, Dragana Nikolić, and Benjamin Sanchez

Abstract Extended reality (XR) technologies refer to mixed reality and virtual reality configurations that augment real or represent fully virtual information in an intuitive and immersive manner, transforming the way we plan, design, construct, and operate built environment assets. XR offers great potential to support and accelerate the transition of built environment practices to a circular economy by supporting decisions based on narrow, slow, close, and regenerate strategies. Narrow strategies use XR to simulate the building process to identify potential issues, reduce material waste, and avoid costly mistakes. Slow strategies use XR to enable construction with durable materials and designing for adaptability to extend the lifespan of buildings. Close strategies use XR to facilitate material recovery and support repurposing and reuse, thus reducing waste. Regenerate strategies use XR as a motivational tool to engage citizens, communities, and professionals in design and management decisions. However, applying XR is not without challenges, including technical and process-related limitations, potential misuse, and a lack of rich digital twins. Future research opportunities include the development of rich and accurate digital twins, ethical and sustainable use of XR technologies, and overcoming technical and logistical challenges through interdisciplinary collaboration and user-friendly and accessible XR hardware and software.

Keywords Extended reality (XR) · Mixed reality (MR) · Virtual reality (VR) · Immersive experiences · Built environment · Circular economy · Digital twins

R. K. Soman (✉)
Delft University of Technology, Delft, the Netherlands
e-mail: r.soman@tudelft.nl

D. Nikolić
University of Reading, Reading, UK

B. Sanchez
Appalachian State University, Boone, NC, USA

C. De Wolf et al. (eds.), *A Circular Built Environment in the Digital Age*, Circular Economy and Sustainability, https://doi.org/10.1007/978-3-031-39675-5_10

10.1 Introduction

Extended reality (XR) is an umbrella term for the kinds of technologies that mediate user perception of digital information. The overarching aim of XR is to augment human perception by giving users compelling, intuitively interactive, and often immersive experiences with little to no awareness on the part of the user of the interference (LaValle 2016). XR technologies can be conceptualised and classified using the virtuality continuum (Milgram and Kishino 1994), a continuous scale spanning from entirely virtual to real worlds (see Fig. 10.1), encompassing varying extents to which real and virtual objects overlap in a mediated environment. We broadly refer to this middle as mixed reality (MR) approaches, although these approaches are also referred to as augmented reality (AR) (the virtual augments the real), augmented virtuality (the real augments the virtual), and diminished reality (removing content from a user's visual environment). XR thus includes various configurations of MR and virtual reality (VR) situated on the virtuality continuum.

10.1.1 Need for XR

We are witnessing unprecedented ways of how we generate, visualise, and share information through more intuitive, wearable, and ever more powerful devices. Within the built environment practices, technologies have long held a promise of offering ways to improve the design and delivery of assets at a greater quality and improved performance. With an urgent call to respond to the challenges of climate change, reduce carbon emissions, and eliminate waste, basing decisions on how to design for future uses increasingly depends on understanding the implications of the status and planned interventions. A network of sensors and real-time data that users generate with their mobile devices begin to give us clues for detecting patterns and simulating and predicting future needs and plan design interventions accordingly (Whyte and Nikolić 2018). While technologies have already supported these kinds of simulations, the trajectory is towards automating these processes by making a more direct link to the readily available sources of data. These novel digital capabilities can transform design and delivery, increase off-site manufacturing, and alter design practices where the delivery is not only for the physical but also for digital assets or digital twins.

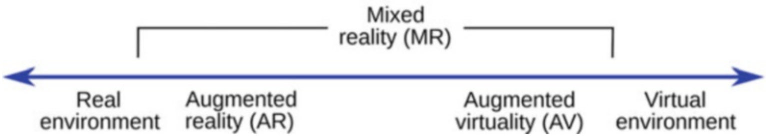

Fig. 10.1 Reality–virtuality continuum. (Adapted from Milgram and Kishino 1994)

When human experiences and behaviours do not lend themselves easily to automation, technologies can furthermore be used to engage people in conversations to share ideas, knowledge, and experiences that may otherwise remain elusive to the designers. In such instances, using visualisation and communication technologies, such as VR or AR, can present a design as something tangible and shareable with clients and prospective users. We can broadly refer to these types of technologies that replicate, present, extend, or augment the real environment and information as XR technologies.

10.1.2 Components of XR System

XR can be viewed as computer-generated environments that are displayed using an array of special hardware to give users compelling, intuitively interactive, and – when relevant – immersive experiences. The XR medium is a combination of output and input devices and plays a large part in shaping user experience. For example, input devices enable users to interact with the virtual world and may also track the user's movement, while output devices display information and respond to the user's input. These include (LaValle 2016; Whyte and Nikolić 2018):

1. Displays (output): screens for visuals, or auditory, olfactory, or haptic displays for other sensory experiences.
2. Sensors (input): devices that track the user data (especially movement), such as cameras, accelerometers, gyroscopes, temperature sensors, etc.
3. Control devices (input-interaction): devices that take inputs from user interaction with the virtual world, such as keyboards, mouse, joysticks, game controllers, haptic devices, etc.
4. Computing devices: devices that generate and continuously align or change the virtual world and project the virtual world to the displays, maintaining the correspondence between users' actions in the real world and the virtual world using sensors and control devices.

The choice of XR configuration will largely depend on the context of its application and the nature of the tasks at hand. Discerning the content and perceptual characteristics of the system will further inform the appropriate hardware configuration as the most optimal for achieving the specific outcomes (Nikolić et al. 2019; Whyte and Nikolić 2018).

10.1.3 Working Principle of an XR System

XR or VR has always conveyed an aim of the "realness" of the virtual experience, although the synthetic nature of this "realness" has been the subject of debates. In all XR applications, choices are made about the salient features that offer compelling user experiences such as sense of presence or immersion. For example, as users navigate and experience the real world through the complex interplay of perceptual and sensory inputs where depth perception, movement, smell, or sound all play an important part, XR approximates and replicates this experience by replacing these sensory inputs with the artificial ones provided by visual, olfactory, sound, and motion tracking devices. However, most of the time, multisensory experience of the real world is replaced by a predominantly visual XR. The prevalence of a visual sense in XR has led to a broad classification of XR configurations based on the extent to which the user's field of view is enveloped in virtual information.

10.1.4 Types of XR Systems

Depending on the extent to which the user's field of view is covered by the digital display or the extent to which the user is visually immersed, XR systems can be broadly characterised as fully immersive, semi-immersive, or non-immersive configurations (Whyte and Nikolić 2018). Fully immersive and semi-immersive systems provide virtual experiences by enclosing the user's field of view, either entirely or partially. Specialised hardware, such as head-mounted or surround-screen displays, stereo views, and position-tracking capabilities, are used to create compelling simulations, but this requires a lot of computing power. Systems that are not immersive use common hardware, such as standard monitors and 3D glasses. They are known as "fishtank" or "window-on-a-world" systems and employ the same software as immersive systems, but without covering the user's field of view. These systems may include some immersive features like stereoscopic viewing, but they do not provide the same level of experience as fully or semi-immersive systems.

XR systems can be for single or multiple users. Head-mounted displays are an example of a single-user XR, which supports the navigation of virtual spaces using tracked controllers and body movements. These systems range from high-end fully immersive displays, like HTC Vive, to lower-end hardware, like Google Cardboard. Conversely, projection-based VR systems that employ large-screen display configurations allow multiple users to experience an XR environment simultaneously. They can also offer fully immersive experiences like enclosed CAVE systems or have more open-footprint semi-immersive applications. Recent software developments in MR have enabled multi-user experiences in head-mounted displays, where users can share the same virtual environment and interact with each other in real time. Tracking user movements and gaze enhances these experiences. Choosing the level of immersion and user participation will depend on the intended users, goals, and tasks for the XR system. Understanding these factors will inform the development of effective XR experiences.

10.2 Existing XR Applications in the Built Environment Life Cycle

The use of immersive and augmented visualisation is changing how we interact with the built environment, presenting new challenges for professionals in planning, architecture, engineering, construction, operations, and deconstruction. Collaboration across diverse roles, goals, and expertise can be facilitated using XR technologies, which enable intuitive and clear visualisation of project information, leading to easier consensus on complex projects (Nikolić and Whyte 2021). The following subsections describe how XR technologies have been used in different life cycle stages of a construction project.

10.2.1 Design Phase

XR technologies have been mostly used to support teams in making decisions during the design phase. For example, 3D interactive visualisation using XR has been more effective in increasing the users' accuracy, perception, and memory in understanding the designs (Calderon-Hernandez et al. 2019; Roupé et al. 2016). From a cognitive viewpoint, XR offers more effective visualisation compared to viewing 3D information on 2D monitors, deemed to be cognitively more demanding (Hermund et al. 2018). This principle has been used in collaborative visualisation for participatory design, crowd simulations, and interactive visualisation of simulation data such as structural simulation, lighting simulations, and fluid dynamics simulations (Safikhani et al. 2022). Studies have revealed that the use of XR is effective in design for presenting different design configurations.

XR provides a realistic, safe, and fully manipulable testing environment through interactions with the virtual environment. BIM workflows can be completed with real-time interactive visualisation enabling communication and collaboration with stakeholders who may not possess BIM skills (Prouzeau et al. 2020). For example, lighting design done based on the designer's previous experience or simulation results (Natephra et al. 2017) may not account for the intended users' experience. Instead, XR can leverage user feedback from occupants during the lighting design process (Natephra et al. 2017; Wong et al. 2019). Similarly, quantitative metrics, such as movement speed and directions, can also be incorporated in VR-based human-building interaction studies to improve the design. Biometric sensors such as electroencephalograms, galvanic skin responses, and facial- or vision-based electromyography can be used as measurements. Further, risk situations and the safety of workers can be effectively assessed with VR. Specific aspects that imperil virtual labour can be easily identified and adjusted (Casini 2022). How people experience these spaces and interact with each other can directly influence people's health and comfort. Data observed during XR interactive simulations can, in turn, be collected and analysed (Casini 2022; Wong et al. 2020).

During the design phase of construction, VR technology is used more often than other XR configurations. VR offers immersive, 1:1 scale representations of the final structure, which can be experienced by a single user wearing a head-mounted display, or by multiple users viewing the environment on large screens. The level of immersion in these VR environments can vary, with some using stereoscopic displays for a highly realistic experience and others using monoscopic displays for a less intense but still informative experience. Ultimately, the choice of VR technology used during the design phase of construction will depend on the specific application and the users' needs.

10.2.2 Construction Phase

XR-supported communication can be used to extend or replace the traditional concept of face-to-face communication in projects. For example, in a study by Du et al. (2016), a cloud-based multi-user XR communication platform enhanced interpersonal interactions and supported users in performing better on assigned construction tasks than users in the traditional desktop application. The use of collaborative VR configurations offers communication experiences comparable to traditional face-to-face communication, particularly in terms of discussion quality (level of effectiveness and satisfaction experienced), communication richness (detailed responses and compelling messages), and openness (enjoyableness and open-mindedness). However, in-person communication still tends to outperform remote alternatives with higher accuracy due to a strong reliance on social cues and the weak human–human interaction in the current generation of XR (Abbas et al. 2019). Prior studies have identified that XR could lead to better problem-finding performance (Wu et al. 2019), improving communication efficiency among stakeholders and motivating them to share a common vision for the project as a joint walk-through (Du et al. 2016; Shi et al. 2016).

In addition to collaborative tasks, XR has been used in construction planning, site planning, and execution visualisation. VR, for example, can play a significant role in the design of construction workplace scenarios (Yu et al. 2019) and can be used both as a learning environment for workers and as a planning tool for construction managers. To create a virtual construction site for information sharing between disciplines, construction teams can visualise the execution methods on a construction site to better understand the procedures (Tran 2019). The 4D simulation workflow in VR can provide a supportive environment for constructability analysis meetings (Boton 2018). However, a proper workflow is required to update the virtual environment according to the current design state (Vincke et al. 2019).

AR is widely used during the construction phase to visualise the design of a building or infrastructure before it is built on the site, allowing stakeholders to identify any issues or discrepancies early on and make necessary changes. This can help reduce the risk of costly delays or rework during construction. AR can also be used to create virtual mock-ups of the construction site, which can be helpful for planning logistics and identifying potential issues (Chalhoub and Ayer 2019). Additionally, there are AR applications that provide stepped instructions and guidance to workers on site, helping to reduce the risk of errors or accidents (Kwiatek et al. 2019; Lin et al. 2020). Furthermore, AR can be used to check that construction work is being completed to the correct specifications and standards, enabling quality control and ensuring that the final product meets the desired standards (Zhou et al. 2017).

Single-user and multi-user VR systems are commonly used in the office to visualise the design of a building or infrastructure, identify potential issues, and create virtual mock-ups of the construction. This allows stakeholders to assess the design and plan for any necessary changes before the construction phase begins. In contrast, single-user AR is typically used on the construction site, overlaying digital information onto the real world and assisting with various tasks. Head-mounted displays and window-on-the-world displays can deliver AR content on the construction site. While head-mounted displays offer a more immersive experience, window-on-the-world displays are often preferred due to cost and safety considerations on the construction site. These devices allow workers to see digital information while maintaining a clear view of their surroundings.

10.2.3 Operations and End-of-Life

The use of XR in the operations and end-of-life stage lags behind its use in design and construction stages but offers great potential for facility managers to enhance information retrieval and visualisation of maintenance-related issues. In operations and maintenance use cases, AR has been explored more than VR to support tasks that require an overlay of virtual information over existing assets. For example, during maintenance interventions, technicians can use AR to augment their view of the physical world with overlaid digital content. AR presents information in a context-aware and more comprehensible manner, allowing more effective operations and flexibility in workers' deployment. Manuri et al. (2019) proposed an AR-based system to help the user detect and avoid errors during the maintenance process.

One of the most common applications of XR is certainly that of remote maintenance. Colleagues and experts can see the direct view captured by the operator's AR device on site and send back augmented support information back to the operator along with voice instructions. XR allows facility managers to enhance data visualisation by displaying information right on the field. XR allows the device to estimate the location and orientation of the user. Localisation is performed via global navigation satellite system (GNSS) positioning and/or by comparing the user's perspective to BIM based on deep learning computation (Casini 2022). Wearable devices can enable a collaborative workspace between different professionals. On-site and remote team members can consult with each other. XR allows the creation of collaborative environments where several people, who may even be in different places, can walk around and simultaneously interact with a virtual 3D model (Lee and Yoo 2021).

In addition, AR is being used to preview renovations and retrofit interventions (Casini 2022). With AR, the user can use the screen of a smartphone or tablet to project a "digital window" that overlays the BIM model of an object. Mobile AR applications such as AirMeasure and MeasureKit enable direct measurement of objects directly on the screen of the device. AR solutions can also support the scheduling and planning of building renovations. AR-enhanced visualisation of non-visual data can be a useful cognitive aid for identifying the information needed for decision-making (Meža et al. 2014). Chung et al. (2018) presented a study in which AR-based smart facility management systems demonstrated faster and easier access to information. Alonso-Rosa et al. (2020) presented a monitoring energy system based on mobile AR. AR systems can also overlay the results of building thermal or fluid dynamics simulations on the virtual model or project those in the real environment.

XR technologies can aid in the efficient disassembly and material recovery process during end of life. They are used to support reversible BIM and BIM-based selective disassembly planning for buildings (SDPB). Reversible BIM is a virtual platform that estimates and visualises the degree of reversibility at a component level (Durmisevic et al. 2021). SDPB evaluates BIM disassembly models to optimise disassembly sequence plans and program deconstruction works (Sanchez et al. 2021). In these approaches, XR can provide step-by-step instructions and guidance to workers, reducing the risk of errors and accidents (Kwiatek et al. 2019; Lin et al. 2020). XR can also be used for disassembly sequencing and communication, helping workers identify recovered materials and how they can be reused or recycled (Frizziero et al. 2019). Additionally, XR can provide visual cues and feedback during the disassembly process, assisting workers in identifying the correct tools and techniques for specific building components (Eswaran et al. 2023).

10.3 Leveraging XR for Circular Strategies

This section discusses how XR technologies could foster a transition to a circular economy, especially when applied in tandem with the circular strategies of regenerate, narrow, slow, and close (see Table 10.1).

10.3.1 Regenerate

The regenerate principle focuses on creating sustainable systems that actively restore and enhance their environments, and XR technologies can play a crucial role in enabling such strategies. By facilitating collaboration among professionals, users, and citizens, XR can be utilised for various purposes, including design, participation,

Table 10.1 Summary of existing XR research categorised by circular strategies

		Design	Construct	Operate	Deconstruct
Regenerate	Stimulate human nature and biodiversity	Ball et al. (2008) and Chandler et al. (2022)			
	Use healthy and renewable resources	Kamel Boulos et al. (2017)			
Narrow	Reduce primary input	Parry and Guy (2021) and Wibranek and Tessmann (2023)	Farghaly et al. (2021)	Wibranek and Tessmann (2023)	Farghaly et al. (2021)
	Design for performance	Fukuda et al. (2019), Rezvani et al. (2023) and Banfi et al. (2022)			
	Improve efficiency	Natephra et al. (2017)	Chen and Huang (2013)	Banfi et al. (2022) and Scorpio et al. (2020)	
Slow	Design for long life	Dembski et al. (2019)			
	Design for reversibility				Kunic and Naboni (2022)
	Lifetime extension	Li et al. (2022)		Alavi et al. (2021) and Corneli et al. (2019)	Carbonari et al. (2022), Li et al. (2022) and Gheisari et al. (2016)
	Smart use of space			Kunic and Naboni (2022)	
	Deliver access and performance			Issa and Olbina (2015)	
	Reuse				Parry and Guy (2021)
Close	Recycle			Do et al. (2020) and Mohamad et al. (2021)	
	Urban mining	O'Grady et al. (2021)	Calderon-Hernandez (2018) and Lin et al. (2019)		Frizziero et al. (2019) and Eswaran et al. (2023)
	Track and trace resources			Munaro and Tavares (2021)	

and promoting pro-environmental behaviours. In urban planning and design, head-mounted displays such as OculusRift paired with the powerful Esri CityEngine have been used to engage citizens and communities in evaluating neighbourhood walkability and street noise levels (Kamel Boulos et al. 2017), as well as urban resource allocation, disaster planning, and environmental protection (Chen et al. 2013; Vanegas et al. 2009). In environmental planning applications, for example, fully immersive single-user VR configurations may be used to create a stronger sense of presence to evoke emotional responses when the goal is for participants to act or make behaviour-related decisions (Ball et al. 2008). In the context of land use and biodiversity, Chandler et al. (2022) have explored dynamic audio-temporal virtual landscapes simulating seasonal changes in VR to offer users a visceral experience of these complex dynamics and build stakeholder empathy. In informing and aligning often diverse perceptions on environment and landscape values, XR and simulation technologies can support a constructive debate about alternative options for design and management decisions (Griffon et al. 2011).

10.3.2 Narrow

Narrow strategies focus on optimising specific aspects of a system or process, often leading to incremental improvements. In the context of sustainable architecture and construction, this can involve enhancing resource efficiency, building performance, and user engagement, among others (Çetin et al. 2021). XR technologies can contribute to these improvements, including supporting decision-making with data-intensive simulations, creating high-performing buildings, increasing user engagement, and facilitating renovations for better resource use.

To improve resource efficiency, multiple scenarios can be developed to improve resource efficiency using state-of-the-art modelling and machine learning methods. However, the results of these simulations and models are data-intensive and multi-dimensional, adding complexity for the array of stakeholders in the decision-making process. XR technology can represent these data-intensive results more meaningfully to support decision-making (Dembski et al. 2019). For example, complex computational fluid dynamics models can be simplified using AR to enable users to create high-performing buildings without compromising design requirements (Fukuda et al. 2019).

XR technologies have been used to create high-performing buildings. They have been used to convey data on energy performance, thermal comfort, and lighting from real environments and the BIM models and present them to users more intuitively to improve building performance and user comfort (Banfi et al. 2022). XR technologies combined with BIM and game engines can offer interactive visualisation to support the design of highly efficient lighting by comparing multiple lighting configurations. This can then be combined with user engagement studies to create the best lighting scenarios both at a building and a city scale (Scorpio et al. 2020), where users can change, move, and rotate fixtures (Natephra et al. 2017). Furthermore, the efficiency of new building construction has also been influenced by XR technologies through logistics and construction simulations (Chen and Huang 2013).

XR also contributes to high-performance designs through increased user engagement by offering novel ways to perceive BIM information. VR can present the BIM model through the lens of human experience and perception, allowing for design assessments of issues such as traffic sign sensitivity, road marking, highway landscaping, traffic safety, lane glare, and more (Rezvani et al. 2023). As AR combines the real world with virtual information, mobile applications of AR can scan the real world and measure and identify the materials of existing stock. This information is then connected to design algorithms to promote the integration of pre-used components in a new building, thereby reducing the primary resource needs (Wibranek and Tessmann 2023). Finally, combining XR technologies and image processing techniques creates as-built representations of existing assets, generating material databases for future buildings (Sato et al. 2016).

XR technology has also increased existing building reuse through better renovation. As it can display virtual models of alternative design scenarios superimposed over the existing physical facilitation, combining BIM with MR can speed up and improve the quality of renovation design processes (Carbonari et al. 2022). Old buildings are often renovated with complicated site constraints, multiple interests, and limited capital costs. Therefore, the transformation process has always encouraged stakeholders to participate in improving the design's effectiveness. Tangible user interfaces made up of physical models further simplify the operation. However, most designs are projected, which does not provide a realistic interactive experience. Interactivity and clear visualisation are two advantages of XR technology. Studies have established that using the participatory design approach of XR technology with tangible models will provide a powerful platform for engaging stakeholders in renovating old buildings (Li et al. 2022). In this regard, Gheisari et al. (2016) developed a methodology of a semi-augmented-reality tool, using BIM and panorama, for a building renovation project. They concluded that superimposing the building information models using an augmented panoramic environment provides construction personnel with a simple way to access their required information in a natural, interactive, and location-independent virtual environment.

10.3.3 Slow

As with the narrow strategy, XR use encompasses improving assets' life cycle, design for reversibility, adaptability, and reconfigurability to support the slow strategy.

XR technologies can act as an interface for building digital twins and be used in facility management to extend the asset's service life. Maintenance activities are improved by providing the location of malfunctioning equipment and appropriate and reliable information, and downtime is reduced. Such integration will help the facility managers in optimising building maintenance strategies and decision-making (Alavi et al. 2021). The main challenge in intensifying asset use and extending their valuable service life is the retrieval of specific data during the life cycle of buildings. However, generating and updating information required for operating buildings is costly and the inventory requires thousands of person-hours. To address these concerns, XR combined with deep learning techniques has been used to retrieve the asset data for a real-time check on the status. The proposed system aims to achieve some degree of automation in the data collection process, particularly compared to current inventory procedures that still require lengthy post-processing (Corneli et al. 2019). The applications of AR in facility management include intelligent fault diagnosis, visualised operation guidance, situational awareness, and building performance monitoring (Issa and Olbina 2015).

Another example is the use of XR for design for reversibility, adaptability, and reconfigurability. Kunic and Naboni (2022) developed a methodology for collaborative design and construction of reconfigurable wood structures in an AR environment. They concluded that using AR can drastically increase the efficiency in the process of assembly and reassembly of reconfigurable systems.

10.3.4 Close

The close strategy in the built environment revolves around efficient resource use, recycling, and reusing materials, ultimately minimising waste and promoting sustainability. The following paragraphs delve into how XR technologies can facilitate recycling by training people to identify waste types, track resources throughout a built asset's life cycle, and support urban mining by visualising the bill of quantities and material stock. Moreover, XR can aid in disassembly sequencing and communication, providing visual cues and feedback to ensure effective recovery and implementation of circular economy design.

For recycling, XR has been effective in training people to identify different wastes and dispose of them accordingly. This application uses interaction cues and visual and auditory feedback to help the user learn proper recycling behaviour (Do et al. 2020). The users are guided by these visual interaction cues as to which elements they can interact with, where to go in navigation, and what information is available about the content in the proposed AR application called Recycl-AR. The visual interaction cues framework comprises four components: task, markedness, trigger, and characteristic (Mohamad et al. 2021). In addition, there is work on using AR to use construction waste in new projects effectively. This has been tested to create a wooden structure using scrap timber beams of different cross sections. Furthermore, the same method has been tested to work with different lengths of waste material too. Instead of the more traditional method of designing and documenting, the designer had a more flexible relationship with the design and the digitised inventory of parts. This technique reflects a fundamental shift in the design paradigm, where designers work with a blank slate of materials where cost or structural competence is the only constraining factor (Parry and Guy 2021).

In addition to recycling, XR can help track resources over the life cycle of built assets. This helps to create a material database with high provenance. The materials passports can be used to obtain a comprehensive set of information and tracking in order to reuse and recycle building materials (Munaro and Tavares 2021). However, it is difficult to maintain up-to-date material passports. As stated earlier, AR has already been used for facility management tasks (Alavi et al. 2021; Chung et al. 2018). The materials passports can thus be integrated with hybrid reality-based facility management systems to improve data maintenance. IT will also be easy to retrieve the details of an asset as it is localised and contextualised in an XR environment.

Furthermore, XR technologies can effectively close and support urban mining. For example, studies have begun to explore how VR tools can allow building designers to see and implement their plans for improving CE design. The XR tools can support users to visualise the bill of quantities and material stock embedded within the studied building, furthering our knowledge of concepts such as buildings as material banks. Furthermore, they allow building designers to see and implement their plans for improving CE design (O'Grady et al. 2021). In addition, XR can be used for disassembly sequencing and communication (Frizziero et al. 2019). The construction sector has already used AR-based construction sequencing for assembling buildings (Calderon-Hernandez 2018; Lin et al. 2019). Lessons from the manufacturing sector show that creating disassembly sequences for construction and embedding the (dis)assembly sequence in the materials passports for effective recovery hold great potential. XR can provide value as it can provide visual cues and feedback during the disassembly (Eswaran et al. 2023).

10.4 Circular Economy Examples of XR in Construction Practice

The upcoming section presents three examples of how XR is used in the construction industry to enable circular transition strategies.

10.4.1 Collaborative Visualisation of Design

Collaborative design visualisation in the construction industry is a process that brings together different experts, such as architects, engineers, contractors, and clients, to work together in the design and construction of buildings and infrastructure projects. Collaborative design visualisation in the construction industry is achieved using XR semi-immersive technologies enabling real-time collaboration among experts. By working together, these experts can identify areas of the design that can be optimised for resource efficiency and the use of fewer inputs in products.

For example, through collaborative visualisation, they can detect and eliminate redundancies, reduce waste, and identify areas where fewer resources could be used while maintaining the desired functionality and performance. This contributes to the narrow strategy of circular transition by reducing the overall environmental impact of the built environment and enabling the sustainable use of resources.

An example of collaborative design visualisation is 3D MOVE (Mobile Visualisation Environment), developed at the University of Reading. It is a collaborative tool for multiple users to interact with and explore full-scale 3D models and built environments (see Fig. 10.2). A study of this technology showed that using collaborative VR environments like 3D MOVE can give project teams more ability to question, evaluate, and justify design decisions (Nikolić et al. 2019), resulting in improved design performance and efficiency and reducing resources needed to build the asset. There are commercial offerings that provide collaborative design visualisation capabilities for the construction industry. For example, Mission Room and Fulcro Fullmax are two companies that offer semi-immersive hardware solutions for construction projects. They use software solutions such as Revitzo, Unity Reflect, BIM 360, and Fuzor for their software workflows.

Fig. 10.2 Collaborative visualisation in 3D Move. (Nikolić et al. 2019)

10.4.2 Construction Production Control Rooms

Construction production control rooms are collaborative digital interfaces that offer real-time project information and efficient construction management. These non-immersive XR-based rooms serve as interfaces to the construction stage digital twins. They use fishtank displays, which present information in a two-dimensional manner like a regular computer screen. Construction production control rooms play an essential role in implementing narrow and close strategies in construction projects. They provide real-time project information, including Gantt charts, schedules, and resource allocation, leading to efficient use of resources, time, and budget while minimising unnecessary delays or rework. By reducing rework, they help to minimise waste and maximise the value of materials, closing resource loops. They optimise resource use by identifying underutilised or overused areas and making necessary adjustments. Overall, production control rooms are valuable for promoting narrow and close strategies in construction projects by enabling real-time data tracking, interpretation, and collaboration for efficient construction management. The AEC Production Control Room (see Fig. 10.3) is an example of a collaborative visualisation platform that aims to make the UK construction industry more efficient and proactive by providing a scalable and repeatable platform for construction management and reporting (Farghaly et al. 2021).

10.4.3 Construction AR

Construction AR enables construction professionals to interact with digital models and information overlaid onto the physical environment, which can play a significant role in helping the industry achieve circular transition strategies that include narrow, slow, and close concepts. In the narrow approach, AR can optimise resource use by

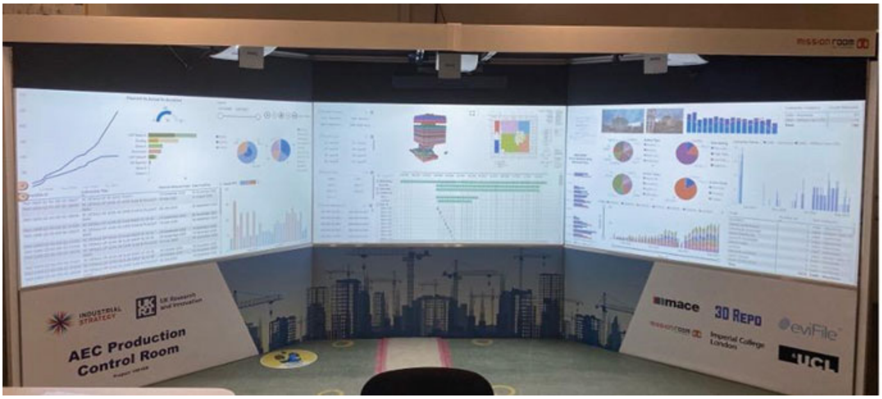

Fig. 10.3 Collaborative data visualisation in AEC Production Control Room

providing real-time data on resource availability, allocation, and utilisation, improving resource efficiency, narrowing resource flows, and reducing waste. In the slow approach, AR can help construction teams improve project planning, prevent delays, rework, and material waste, and provide progress tracking and documentation features that ensure all team members capture project progress at the exact same location over time. In the close approach, AR can help with the recovery and reuse of materials from construction sites by providing real-time data on the location and condition of building materials, which can support the identification and tracking of materials for potential reuse or recycling, closing the loop of material use and contributing to a circular transition.

There are several companies offering AR solutions for the construction industry. Arvizio provides features such as 3D model and LiDAR scan import, processing, optimisation, and hybrid rendering to build digital twins and facilitate use cases such as design reviews, spatial data management, marketing demos, and quality assurance inspections. Innovative construction technology (ICT) offers ICT Tracker, an AR software for contractors to streamline project installation tracking and reporting. This app provides comprehensive data in easy-to-read reports and allows contractors to compare BIM or 3D models against current installations, preventing margin slip. VisualLive offers AR solutions on HoloLens 1 & 2, Android, and iOS, enabling AEC professionals to push design models onto their AR devices and bring their computer-aided design (CAD) or BIM onto the construction site. Lastly, the XYZ Reality Atom is a powerful engineering tool that combines a construction safety headset, AR displays, and in-built computing power (see Fig. 10.4). It uses laser-based tracking technology to position 3D design models with millimetre accuracy, allowing users to view holograms of models positioned within construction tolerances.

Fig. 10.4 Augmented visualisation and construction site using XYZ Reality Atom

10.5 Discussion

XR technologies have significant, yet untapped potential to support and accelerate the transition to a circular economy. XR provides intuitive, immersive, and interactive experiences of imagined futures that can support more informed decision-making and optimise the use of resources. XR can help the construction sector transition to a circular economy by enabling more effective and informed design and construction processes while reducing waste and extending the lifespan of buildings. With narrow strategies, VR and AR can be used to simulate the building process and identify potential issues, helping construction companies avoid costly mistakes and reduce material waste. Slow strategies, such as building with durable materials and designing for adaptability, allow buildings to have a longer lifespan, reducing the need for new construction. Close strategies, such as using XR to facilitate deconstruction and material recovery at the end of a building's life, help ensure that materials can be repurposed and reused, further reducing waste and supporting a circular economy. Finally, for regeneration strategies, XR can be used as a powerful participatory and motivational tool to engage citizens, communities, and professionals in the design and management decisions of the built environment.

However, there are several limitations to applying XR that warrant further and careful consideration. One major limitation is the slow development of rich digital twins of buildings, infrastructure, and other physical assets. Digital twins are crucial for the success of XR in the built environment because they provide detailed and accurate representations of physical assets, which are essential for creating realistic and useful XR experiences. Rich digital twins enable XR technologies to provide dynamic and responsive representations of the built environment, which can enable more efficient and effective design, construction, and operation of the built environment. Without access to rich digital twins, XR technologies may not be able to provide the necessary level of detail and accuracy for effective use in the circular economy. Another limitation is the potential for misuse or abuse of XR technologies. It is essential to ensure that the virtual models of proposed circular systems created by XR technologies reduce domain-specific biases but are based on realistic and sustainable principles, which reflect the needs and preferences of stakeholders, such as workers, consumers, and the environment. Misleading or ineffective designs can have negative impacts on the success of the circular economy and may even be harmful. Finally, there are technical and logistical challenges associated with implementing XR technologies in the circular economy. Small and medium-sized enterprises may face barriers to adoption and use due to the need for specialised hardware, software, and training, which require significant resources and expertise. There may also be challenges in integrating XR technologies with existing systems and processes in the circular economy, which need to be addressed to ensure that the technologies can be implemented effectively and generate the desired benefits. However, with careful planning and investment, these challenges can be overcome, and XR technologies can play a key role in accelerating the transition to a circular economy.

Future research opportunities for XR in the circular economy include the development of rich and accurate digital twins, ensuring ethical and sustainable use of XR technologies, and overcoming technical and logistical challenges. To address these challenges, interdisciplinary collaboration is necessary, involving experts in architecture, engineering, computer science, sustainability, and social sciences. Additionally, the development of user-friendly and accessible XR hardware and software is crucial, with the potential for Metaverse-like technologies to provide inclusive and intuitive interfaces for a wider range of stakeholders. However, the development of XR software must be guided by the principles of circularity and sustainability and be evaluated in terms of their social, economic, and environmental impacts to ensure that they contribute to the broader goals of a more circular and resilient built environment. It is essential to remain sceptical of the potential for XR technologies to address the challenges of the circular economy and to design and evaluate them through a participatory and inclusive process that reflects the diversity of perspectives and experiences of those who will be using the technologies.

10.6 Key Takeaways

- Extended reality (XR) can help implement the regenerate principle by fostering collaboration, promoting pro-environmental behaviours, and supporting constructive debates on design and management decisions.
- XR can enable data-driven decision-making in the narrow strategy for a circular economy, contributing to high-performing buildings, increased user engagement, and better resource utilisation.
- XR can support the slow strategy for a circular economy by enhancing asset life cycle management and promoting design for reversibility, adaptability, and reconfigurability.
- XR can facilitate recycling efforts by improving waste identification, resource tracking, and urban mining visualisation, while also aiding in disassembly sequencing and communication.
- The lack of rich digital twins of physical assets, inadequate use of XR technologies, and technical and logistical challenges still tend to limit the effective implementation of XR in the circular economy and need to be addressed.

Acknowledgements Research work of the first and third authors contributing to this chapter was conducted at the Future Cities Lab Global at Singapore-ETH Centre and ETH Zurich. Future Cities Lab Global is supported and funded by the National Research Foundation, Prime Minister's Office, Singapore, under its Campus for Research Excellence and Technological Enterprise (CREATE) programme and ETH Zurich, with additional contributions from the National University of Singapore, Nanyang Technological University, Singapore, and the Singapore University of Technology and Design.

References

Abbas A, Choi M, Seo J, Cha SH, Li H (2019) Effectiveness of immersive virtual reality-based communication for construction projects. KSCE J Civ Eng 23:4972. https://doi.org/10.1007/s12205-019-0898-0

AirMeasure. http://airmeasure.com/. Accessed 15 May 2023

Alavi H, Forcada N, Fan SL, San W (2021) BIM-based augmented reality for facility maintenance management. In: Proceedings of the 2021 European conference on Computing in Construction, pp 431–438. https://doi.org/10.35490/EC3.2021.180

Alonso-Rosa M, Gil-de-Castro A, Moreno-Munoz A, Garrido-Zafra J, Gutierrez-Ballesteros E, Cañete-Carmona E (2020) An IoT based mobile augmented reality application for energy visualization in buildings environments. Appl Sci 10(2). https://doi.org/10.3390/app10020600

Ball J, Capanni N, Watt S (2008) Virtual reality for mutual understanding in landscape planning. Int J Soc Sci 2(2):78–88

Banfi F, Brumana R, Salvalai G, Previtali M (2022) Digital twin and cloud BIM-XR platform development: from scan-to-BIM-to-DT process to a 4D multi-user live app to improve building comfort, efficiency and costs. Energies 15(12):4497. https://doi.org/10.3390/en15124497

Boton C (2018) Supporting constructability analysis meetings with immersive virtual reality-based collaborative BIM 4D simulation. Autom Constr 96:1–15. https://doi.org/10.1016/j.autcon.2018.08.020

Calderon-Hernandez C (2018) Lean, BIM and augmented reality applied in the design and construction phase: a literature review. Int J Innov Manag Technol 60–63. https://doi.org/10.18178/ijimt.2018.9.1.788

Calderon-Hernandez C, Paes D, Irizarry J, Brioso X (2019) Comparing virtual reality and 2-dimensional drawings for the visualization of a construction project. In: Computing in civil engineering 2019, pp 17–24. https://doi.org/10.1061/9780784482421.003

Carbonari A, Franco C, Naticchia B, Spegni F, Vaccarini M (2022) A mixed reality application for the on-site assessment of building renovation: development and testing. Sustainability 14(20). https://doi.org/10.3390/su142013239

Casini M (2022) Extended reality for smart building operation and maintenance: a review. Energies 15(10). https://doi.org/10.3390/en15103785

Çetin S, De Wolf C, Bocken N (2021) Circular digital built environment: an emerging framework. Sustainability 13(11):6348. https://doi.org/10.3390/su13116348

Chalhoub J, Ayer SK (2019) Exploring the performance of an augmented reality application for construction layout tasks. Multimed Tools Appl 78(24):35075–35098. https://doi.org/10.1007/s11042-019-08063-5

Chandler T, Richards AE, Jenny B, Dickson F, Huang J, Klippel A, Neylan M, Wang F, Prober SM (2022) Immersive landscapes: modeling ecosystem reference conditions in virtual reality. Landsc Ecol 37(5):1293–1309. https://doi.org/10.1007/s10980-021-01313-8

Chen HM, Huang PH (2013) 3D AR-based modeling for discrete-event simulation of transport operations in construction. Autom Constr 33:123–136. https://doi.org/10.1016/j.autcon.2012.09.015

Chen M, Lin H, Hu M, He L, Zhang C (2013) Real-geographic-scenario-based virtual social environments: integrating geography with social research. Environ Plan B 40(6):1103–1121. https://doi.org/10.1068/b38160

Chung S, Kwon S, Moon D, Ko T (2018) Smart facility management systems utilizing open BIM and augmented/virtual reality. In: 34th International Symposium on Automation and Robotics in Construction, Taipei, Taiwan. https://doi.org/10.22260/ISARC2018/0118

Corneli A, Naticchia B, Cabonari A, Bosché F (2019) Augmented reality and deep learning towards the management of secondary building assets. In: 36th International Symposium on Automation and Robotics in Construction, Banff, AB, Canada. https://doi.org/10.22260/ISARC2019/0045

Dembski F, Wössner U, Letzgus M (2019) The digital twin tackling urban challenges with models, spatial analysis and numerical simulations in immersive virtual environments. Blucher Des Proc:795–804. https://doi.org/10.5151/proceedings-ecaadesigradi2019_334

Do TD, Yu DS, Katz A, McMahan RP (2020) Virtual reality training for proper recycling behaviors. In: ICAT-EGVE 2020 – international conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments. https://doi.org/10.2312/EGVE.20201284

Du J, Shi Y, Mei C, Quarles J, Yan W (2016) Communication by interaction: a multiplayer VR environment for building walkthroughs. In: Construction research congress 2016, pp 2281–2290. https://doi.org/10.1061/9780784479827.227

Durmisevic E, Guerriero A, Boje C, Domange B, Bosch G (2021) Development of a conceptual digital deconstruction platform with integrated reversible BIM to aid decision making and facilitate a circular economy. In: Proceedings of the Joint Conference CIB W78-LDAC, Luxembourg, pp 11–15

Eswaran M, Gulivindala AK, Inkulu AK, Raju Bahubalendruni MVA (2023) Augmented reality-based guidance in product assembly and maintenance/repair perspective: a state-of-the-art review on challenges and opportunities. Expert Syst Appl 213:118983

Farghaly K, Soman RK, Whyte J (2021) Visualizing real-time information through a construction production control room. In: Proceedings of the 2021 European conference on Computing in Construction, vol 2, pp 415–422. https://doi.org/10.35490/EC3.2021.169

Frizziero L, Liverani A, Caligiana G, Donnici G, Chinaglia L (2019) Design for disassembly (DfD) and augmented reality (AR): case study applied to a gearbox. Mach Des 7(2):29. https://doi.org/10.3390/machines7020029

Fukuda T, Yokoi K, Yabuki N, Motamedi A (2019) An indoor thermal environment design system for renovation using augmented reality. J Comput Des Eng 6(2):179–188. https://doi.org/10.1016/j.jcde.2018.05.007

Gheisari M, Foroughi Sabzevar M, Chen P, Irizzary J (2016) Integrating BIM and panorama to create a semi-augmented-reality experience of a construction site. Int J Constr Educ Res 12(4): 303–316

Griffon S, Nespoulous A, Cheylan JP, Marty P, Auclair D (2011) Virtual reality for cultural landscape visualization. Virtual Reality 15(4):279–294. https://doi.org/10.1007/s10055-010-0160-z

Hermund A, Klint L, Bundgaard T (2018) BIM with VR for architectural simulations building information models in virtual reality as an architectural and urban design tool. In: 6th annual international conference on Architecture and Civil Engineering (ACE 2018). https://doi.org/10.5176/2301-394X_ACE18.152

Issa RRA, Olbina S (eds) (2015) Building information modeling: applications and practices. Am Soc Civil Eng. https://doi.org/10.1061/9780784413982

Kamel Boulos MN, Lu Z, Guerrero P, Jennett C, Steed A (2017) From urban planning and emergency training to Pokémon Go: applications of virtual reality GIS (VRGIS) and augmented reality GIS (ARGIS) in personal, public and environmental health. Int J Health Geogr 16(1):7. https://doi.org/10.1186/s12942-017-0081-0

Kunic A, Naboni R (2022) Collaborative design and construction of reconfigurable wood structures in a mixed reality environment. In: Proceedings of the 25th SIGraDi conference: critical appropriations

Kwiatek C, Sharif M, Li S, Haas C, Walbridge S (2019) Impact of augmented reality and spatial cognition on assembly in construction. Autom Constr 108:102935. https://doi.org/10.1016/j.autcon.2019.102935

LaValle S (2016) Virtual reality. Cambridge University Press

Lee Y, Yoo B (2021) XR collaboration beyond virtual reality: work in the real world. J Comput Des Eng 8(2):756–772. https://doi.org/10.1093/jcde/qwab012

Li J, Lo TT, Guo X, Chen F (2022) Integrating XR and tangible model to enhance old building renovation design. In: Proceedings of ECAADe 2022: co-creating the future – inclusion in and through design, pp 207–216. https://doi.org/10.52842/conf.ecaade.2022.2.207
Lin Z, Petzold F, Hsieh SH (2020) 4D-BIM based real time augmented reality navigation system for tower crane operation. In: Construction research congress 2020, November, Reston, pp. 828–836. https://doi.org/10.1061/9780784482865.088
Lin Z, Petzold F, Ma Z (2019) A real-time 4D augmented reality system for modular construction progress monitoring. In: 36th international symposium on Automation and Robotics in Construction, Banff, AB, Canada. https://doi.org/10.22260/ISARC2019/0100
Manuri F, Pizzigalli A, Sanna A (2019) A state validation system for augmented reality based maintenance procedures. Appl Sci 9(10). https://doi.org/10.3390/app9102115
MeasureKit. https://measurekit.com/. Accessed 15 May 2023
Meža S, Turk Ž, Dolenc M (2014) Component based engineering of a mobile BIM-based augmented reality system. Autom Constr 42:1–12. https://doi.org/10.1016/j.autcon.2014.02.011
Milgram P, Kishino F (1994) A taxonomy of mixed reality visual displays. IEICE Trans Inf Syst 77(12):1321–1329
Mohamad NHR, Ijab MT, Hamid S (2021) Visual interaction cues framework for recycling education using augmented reality. In: 2021 International Conference on Computer Science and Engineering (IC2SE), pp 1–8. https://doi.org/10.1109/IC2SE52832.2021.9791879
Munaro MR, Tavares SF (2021) Materials passport's review: challenges and opportunities toward a circular economy building sector. Built Environ Proj Asset Manag 11(4):767–782. https://doi.org/10.1108/BEPAM-02-2020-0027
Natephra W, Motamedi A, Fukuda T, Yabuki N (2017) Integrating building information modeling and virtual reality development engines for building indoor lighting design. Vis Eng 5(1):19. https://doi.org/10.1186/s40327-017-0058-x
Nikolić D, Maftei L, Whyte J (2019) Becoming familiar: How infrastructure engineers begin to use collaborative virtual reality in their interdisciplinary practice. J Inf Technol Constr 24:489–508. https://doi.org/10.36680/j.itcon.2019.026
Nikolić D, Whyte J (2021) Visualizing a new sustainable world: Toward the next generation of virtual reality in the built environment. Buildings 11(11):Article 11
O'Grady TM, Brajkovich N, Minunno R, Chong HY, Morrison GM (2021) Circular economy and virtual reality in advanced BIM-based prefabricated construction. Energies 14(13):4065. https://doi.org/10.3390/en14134065
Parry C, Guy S (2021) Recycling construction waste material with the use of AR. In: Yuan PF, Yao J, Yan C, Wang X, Leach N (eds) Proceedings of the 2020 DigitalFUTURES. Springer, Singapore, pp 57–67. https://doi.org/10.1007/978-981-33-4400-6_6
Prouzeau A, Wang Y, Ens B, Willett W, Dwyer T (2020) Corsican twin: authoring in situ augmented reality visualisations in virtual reality. In: Proceedings of the international conference on advanced visual interfaces, pp. 1–9. https://doi.org/10.1145/3399715.3399743
Rezvani M, Taghaddos H, Sobhkhiz S, Noghabaei M, Ghorab K (2023) User engagement for sustainable development: how can virtual reality help? In: Walbridge S, Nik-Bakht M, Ng KTW, Shome M, Alam MS, el Damatty A, Lovegrove G (eds) Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021, vol 251, pp 239–249. Springer, Singapore. https://doi.org/10.1007/978-981-19-1029-6_18
Roupé M, Johansson M, Tallgren MV, Jörnebrant F, Tomsa PA (2016) Immersive visualization of building information models. In: Living systems and micro-utopias: towards continuous designing, Proceedings of the 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA 2016), pp 673–682
Safikhani S, Keller S, Schweiger G, Pirker J (2022) Immersive virtual reality for extending the potential of building information modeling in architecture, engineering, and construction sector: systematic review. Int J Digit Earth 15(1):503–526. https://doi.org/10.1080/17538947.2022.2038291

Sanchez B, Rausch C, Haas C, Hartmann T (2021) A framework for BIM-based disassembly models to support reuse of building components. Resour Conserv Recycl 175:105825

Sato Y, Fukuda T, Yabuki N, Michikawa T, Motamedi A (2016) A marker-less augmented reality system using image processing techniques for architecture and urban environment. In: 21st International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA): Living Systems and Micro-Utopias: Towards Continuous Designing, 11

Scorpio M, Laffi R, Masullo M, Ciampi G, Rosato A, Maffei L, Sibilio S (2020) Virtual reality for smart urban lighting design: review, applications and opportunities. Energies 13(15):3809. https://doi.org/10.3390/en13153809

Shi Y, Du J, Lavy S, Zhao D (2016) A multiuser shared virtual environment for facility management. Procedia Eng 145:120–127. https://doi.org/10.1016/j.proeng.2016.04.029

Tran N (2019) Exchange information enhancement in execution method by using virtual reality. ISPRS Int Arch Photogramm Remote Sens Spatial Inf Sci XLII-5(W2):71–75. https://doi.org/10.5194/isprs-archives-XLII-5-W2-71-2019

Vanegas CA, Aliaga DG, Benes B, Waddell P (2009) Visualization of simulated urban spaces: inferring parameterized generation of streets, parcels, and aerial imagery. IEEE Trans Vis Comput Graph 15(3):424–435. https://doi.org/10.1109/TVCG.2008.193

Vincke S, de Lima HR, Bassier M, Vergauwen M (2019) Immersive visualisation of construction site point cloud data, meshes and BIM models in a VR environment using a gaming engine. Int Arch Photogramm Remote Sens Spatial. Inf Sci XLII-5-W2:77–83. https://doi.org/10.5194/isprs-archives-XLII-5-W2-77-2019

Whyte J, Nikolić D (2018) Virtual reality and the built environment, 2nd edn. Routledge. https://doi.org/10.1201/9781315618500

Wibranek B, Tessmann O (2023) Augmented reuse: a mobile app to acquire and provide information about reusable building components for the early design phase. In: Gengnagel C, Baverel O, Betti G, Popescu M, Thomsen MR, Wurm J (eds) Towards radical regeneration. Springer, pp 411–423. https://doi.org/10.1007/978-3-031-13249-0_33

Wong JY, Chun Chieh Y, Yong ST, Chan A, Kok ST, Lau T, Ali M, Gouda E (2020) BIM-VR framework for building information modelling in engineering education. Int J Interact Mob Technol (IJIM) 14:15. https://doi.org/10.3991/ijim.v14i06.13397

Wong MO, Du J, Zhang ZQ, Liu YQ, Chen SM, Lee SH (2019) An experience-based interactive lighting design approach using BIM and VR: a case study. IOP Conf Ser Earth Environ Sci 238(1):012006. https://doi.org/10.1088/1755-1315/238/1/012006

Wu TH, Wu F, Kang SC, Chi HL (2019) Comparison of virtual communication environment for remote BIM model review collaboration. In: ISARC Proceedings, pp 1149–1154

Yu Z, Peng H, Zeng X, Sofi M, Xing H, Zhou Z (2019) Smarter construction site management using the latest information technology. Proc Inst Civil Eng – Civil Eng 172(2):89–95. https://doi.org/10.1680/jcien.18.00030

Zhou Y, Luo H, Yang Y (2017) Implementation of augmented reality for segment displacement inspection during tunneling construction. Autom Constr 82:112–121. https://doi.org/10.1016/j.autcon.2017.02.007

Ranjith K. Soman is an Assistant Professor at TU Delft specialising in digital construction and project management, and an Honorary Research Associate at Imperial College London. His research combines information technology with civil engineering, with a particular focus on using extended reality, knowledge graphs, and artificial intelligence to improve infrastructure sustainability.

Dragana Nikolić is an associate professor in Digital Built Environment at the University of Reading. Her work focuses on advanced digital and visualisation technologies to support and improve design and construction.

Benjamin Sanchez is an Assistant Professor at Appalachian State University, North Carolina, USA. Benjamin's research is focused on the development and implementation of digital technologies (BIM, IoT, LCA, 3D scan-to-BIM) for increasing the performance of construction building projects in terms of sustainability and circular economy.