THE ROLE OF DIGITAL TECHNOLOGIES IN ADVANCING CIRCULAR ECONOMY PRACTICES IN THE AUSTRALIAN CONSTRUCTION INDUSTRY

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The construction industry's ongoing environmental impact demands urgent improvement, driving a strong emphasis on adopting circular economy (CE) principles for their ecological benefits. There is a growing recognition of Digital Technologies (DTs) as facilitators of circular practices. However, the construction industry is known for its slow adoption of technology, primarily due to the resistance of professionals to change. Thus, this research investigates how professionals in the Australian construction and CE sectors perceive the role of DTs in enabling circular practices. Data from 16 semi-structured interviews were analysed using code-based content analysis with NVivo 15. The findings reveal nine key roles of DTs—including acting as guiding platforms, facilitating data collection, tracking materials, optimising design, reducing material usage, enabling material reuse, and improving material flow—supported by technologies such as AI, Additive Manufacturing, Big Data Analytics, BIM, GIS, Digital Twin, Blockchain, IoT, RFID, and Cloud Computing. The identified roles of DTs were mapped against existing CE barriers within the construction industry. This study demonstrates how DT solutions address key CE challenges and provide practical insights for construction stakeholders to advance circular initiatives.

Keywords: circular economy; construction industry; digital technologies; data management; material tracking

INTRODUCTION

The construction industry's resource-intensive operations harm the environment through high energy use, carbon emissions, resource depletion, and excessive waste (Ababio and Lu, 2023). Maintaining current practices risks compromising the environment's ability to support future generations and exacerbates existing environmental issues (Osei-Tutu *et al.,* 2023). The Linear Economy (LE) model in construction covers resource acquisition, material conversion, use, and disposal at End of Life (EOL) (Illankoon and Vithanage, 2023). However, it mainly focuses on material lifespan, often overlooking the post-consumption phase (Cimen, 2021). In contrast, the circular economy (CE) emphasizes maximising material flow and resource efficiency while reducing waste through modularity, regenerative systems, adaptability, reuse, recycling, remanufacturing, and designing for longevity (Ellen

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Macarthur Foundation 2012). The construction industry values the CE for its significant environmental benefits and potential (Pomponi and Moncaster 2017).

A smooth transition to CE depends on key enablers such as industry digitalisation, R&D, stakeholder education, regulatory support, and financial incentives (Shooshtarian *et al.,* 2023). In this context, the complex nature of construction projects, along with the demands of technology, legal frameworks, manufacturing procedures, service outsourcing, and supply chains, has led to the emergence of digital ecosystems (Kovacic, Honic and Sreckovic, 2020). These digital ecosystems have become essential enablers of cooperation, value creation, and the implementation of circular principles. Despite recognising the value of DTs for circular practices, the industry faces slow adoption, primarily due to professionals' resistance to change (Thirumal *et al.,* 2024a). There is growing interest in addressing the slow uptake of DTs in CE practices by grounding research in theories of technology and innovation. In particular, the Diffusion of Innovation (DoI) theory outlines five phases of adoption: knowledge, persuasion, decision, implementation, and confirmation. Specifically, knowledge of utilising DTs for CE practices acts as the precursor, followed by persuasion, where individuals form perceptions based on their understanding, ultimately leading to the decision to adopt or reject it (Thirumal *et al.,* 2024b). However, many studies overlook how such knowledge is reflected in professionals' perceptions, failing to capture nuanced industry perspectives. This slow uptake also raises critical questions about whether current digital solutions truly address the practical challenges of CE implementation. Existing research often overgeneralises the potential of DTs without linking them to specific CE barriers, with limited empirical evidence, especially in Australian construction, on how professionals perceive their role in overcoming these challenges. This study addresses that gap by exploring how industry professionals interpret and engage with DTs in the context of CE implementation.

LITERATURE REVIEW

The importance of DTs to CE adoption in construction projects

DTs are tools or systems that utilise digital processes to create, store, process, and communicate information, thereby enhancing and transforming human and industrial activities through digital data and computation (Puolitaival, Kestle, and Kähkönen, 2018, p. 254). The construction industry is gradually started to adopt DTs, including Geographic Information Systems (GIS), Radio Frequency Identification (RFID) (Yu *et al.,* 2022), Additive Manufacturing (AM), Cloud computing (CC) (Jemal *et al.,* 2023), Building Information Modelling (BIM), Artificial Intelligence (AI), Big data analytics (BDA), Blockchain (BCT), Internet of Things (IoT) and Digital Twins (D/Twins) (Rodrigo *et al.,* 2023) to preserve the built environment's integrity, safety, productivity and circularity. These DTs are vital to the industry's digital transformation, facilitated by technological advancements (Setaki and van Timmeren,2022). DTs can significantly ease the complex, challenging, and diverse shift to circular practices in the industry (Yu *et al.,* 2022).

It is vital to explore whether DTs can help advance the CE by tackling the existing barriers. For instance, the industry faces significant barriers to effective recycling and material reuse due to inadequate tracking mechanisms (Oluleye *et al.,* 2023). If such tracking is lacking, accountability is compromised due to the challenges associated with identifying and obtaining resources from buildings that have been modified or demolished. In addition to tracking issues, the industry is hindered by insufficient waste segregation and surveillance facilities (Oluleye *et al.,* 2023). Current technologies often fall short of efficiently recycling materials, hampered by inadequate material segregation, management barriers, and a lack of disassembly (Osei-Tutu *et al.,* 2023).

Additionally, a lack of a proper data management system exacerbates the challenges associated with circular building practices (Munaro and Tavares, 2023). Existing material databases and modelling tools are limited in their efficacy due to the deficiency of openness and accessibility of technical information regarding building components (Oluleye, Chan, and Antwi-Afari, 2023). Due to these limitations, stakeholders frequently disregard recycling goals or legal obligations. Thus, integrating strategies facilitating the shift to CE remains difficult for construction organisations and key stakeholders (Ababio and Lu, 2023).

Another significant barrier is the absence of integrated methods, instruments, and procedures for managing CDW (Munaro and Tavares, 2023). The industry lacks extensive instruments for identifying, classifying, and verifying recovered or reclaimed materials. The issue of circularity in product design further complicates the implementation of CE practices (Munaro and Tavares, 2023). Thus, the industry suffers from a dearth of material alternatives and complexity in supply chains, which impedes the growth of circular product design (Ababio and Lu, 2023). Moreover, the real-world application of DfD is inhibited by the absence of standardised visualisation tools and spatial geometries (Munaro and Tavares, 2023).

Integrating DTs could bridge the identified challenges by providing real-time, detailed tracking of materials and CDW, thus enhancing the efficiency of reuse and recycling processes and supporting data-driven decision-making regarding waste reduction and resource allocation (Munaro and Tavares, 2023). Moreover, DTs can offer advanced circular design and simulation capabilities, thereby improving the lifecycle management of resources (Cimen 2021). These DTs facilitate the generation and management of data and information required for circular business models. Consequently, digitalisation enables closed material loops and provides precise information regarding the location, state, and accessibility of resources, aiding the transition to a more sustainable CE (Antikainen, Uusitalo, and Kivikytö-Reponen,2018). Recognising this potential, the European Circular Economy Action Plan (2020) emphasizes digitalisation as a key enabler of CE, aiming to reduce material intensity and dependency on virgin resources. In Australia, the CE Interim Report (DCCEEW, 2024) highlights the need for a diverse range of engineering and digital skills to capitalise on CE opportunities fully. However, findings from the Victorian Circular Activator (2022) reveal that many SMEs in the construction sector still rely on conventional waste management methods, with limited integration of DTs in CE initiatives.

METHOD

A comprehensive literature review was conducted to establish theory-based knowledge and identify the potential of DTs in implementing CE practices in construction. Following this, 16 semi-structured interviews were conducted with professionals selected through purposive sampling. All participants had a minimum of two years of experience in CE or DTs within Australian commercial construction projects. They were asked to share their perspectives on the role of DTs in enabling circular practices in construction. This approach ensured a focused and cohesive sample of industry professionals whose insights were most relevant to the research objectives. NVivo 15 was used to open-code the transcripts and conduct code-based content analysis. The codes were then grouped into themes for synthesis and comparison across participants.

FINDINGS AND DISCUSSION

The respondents' years of experience in the construction industry, circular economy, sustainability, and digital technologies are shown in Figure 1.

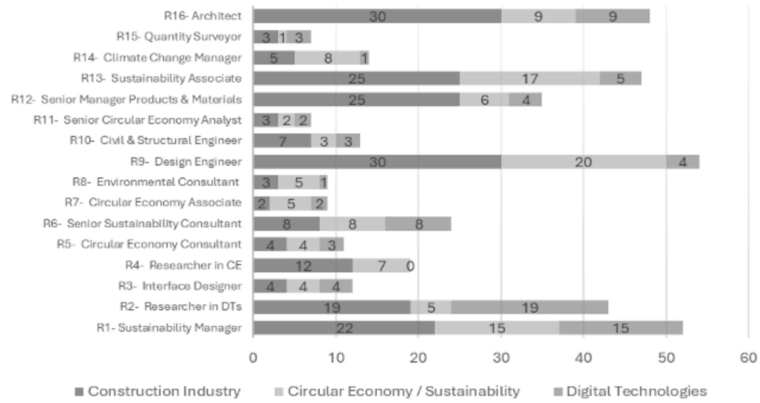
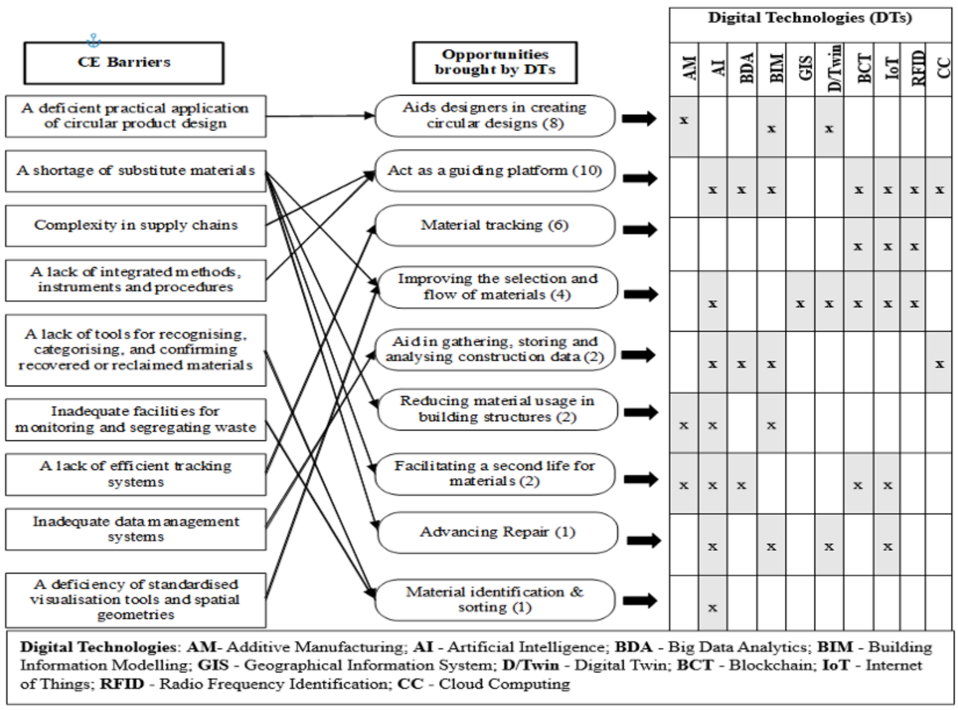


Figure 1: Respondents' years of experience in the construction industry, circular economy or sustainability, and digital technologies

The role of DTs in advancing CE practices in construction, along with the specific DTs enabling them, is presented in Figure 2.

Figure 2: Role of DTs in advancing CE practices in the construction industry



Note: Numbers at the end of each statement indicate the number of respondents who agreed on points.

All respondents consider DTs as an enabler that can aid in implementing CE practices. They believe DTs offer tools for better tracking, managing, and optimising materials, helping reduce waste and improve resource efficiency. The following section outlines the varied perspectives of Australian construction professionals on the role of DTs in advancing CE practices, the barriers they face in implementing or utilising these technologies and their current ability to fully leverage these tools.

Aids designers in creating circular designs

DTs play a key role in helping designers create circular buildings, with early design decisions being crucial to achieving circular outcomes (Banihashemi *et al.,* 2024). This aligns with the views of R1, R4, R9, and R16, who emphasized that developing circular designs supported by DTs can optimise material use while minimising waste. Similarly, R5, R10 and R13 highlighted how DTs facilitate real-time updates to 3D building models whenever modifications are needed. However, insufficient integration of circular principles in product design poses an additional barrier to adopting CE practices (Munaro and Tavares, 2023), suggesting that broader design reforms must complement digital tools to be truly effective. Collectively, these insights underscore the potential of DTs to support circular practices through improved design processes, progress monitoring and evaluation of alternative solutions. Additionally, respondents noted that DTs could support the Design for Disassembly (DfD) principle by facilitating more deliberate sourcing of materials for future projects. It is well established that existing buildings adhere to a traditional cradle-to-grave lifecycle and are not designed to accommodate disassembly or deconstruction. However, R12 noted that such considerations are still not commonly integrated into BIM in current practice, primarily due to limited funding during the design phase. This highlights that while DTs offer potential, financial constraints remain, restricting their practical application. Moreover, all respondents agreed that circular design is rarely considered early and is often addressed only at the end of a building's life. Although DTs such as AM, D/Twins, and BIM can facilitate innovative CE solutions, respondents criticised their limited application, noting that BIM is still primarily used for clash detection rather than more advanced functions. This indicates that shifting towards circular buildings takes time, as it involves aligning models with traditional approaches and enabling design teams to utilise these models to develop more efficient designs.

Act as a guiding platform

DTs have significant potential to streamline construction processes and applications, thereby enhancing efficiency. However, a considerable barrier remains, the absence of integrated instruments, and procedures for implementing CE practices (Munaro and Tavares, 2023). This lack of integration contributes to the complexity of construction supply chains, further hindering efforts to close material loops and achieve circularity (Ababio and Lu, 2023). Addressing these interconnected challenges, R11 emphasized that DTs can act as foundational platforms by enabling the development, integration, and access to a range of supportive tools, functions, and services. R16 further noted that effectively deploying these technologies demands a whole-systems approach that aligns digital innovation with CE goals to reduce fragmentation and enhance material flow. Respondents particularly underscored applications such as the Digital Marketplace, Material Passports, and Digital Product Passports.

Specifically, R7 described the Digital Marketplace as a platform where materials, whether excess, available, or in demand, can be listed, and R5 noted its usefulness in facilitating the supply and demand of materials. These platforms hold significant potential to enhance material exchange and supply chain connectivity; however, current limitations, such as the lack of scheduling for demolition components (Çetin, De Wolf, and Bocken, 2021), hinder their ability to support effective material reuse. In addition, Material Passports (MPs) are static documents exemplified by projects such as the Building as Material Banks (BAMB-EU) and trials conducted by Kennett Builders in Australia. While MPs can aid CE practices, limitations remain, including the lack of a centralised system for material data storage and standardised formats for organising information. This fragmentation highlights data governance and coordination challenges that may limit MPs' effectiveness in promoting circularity. In contrast, Digital Product Passports (DPPs) are designed as dynamic, detailed tools for tracking materials and managing their lifecycle. They are expected to have wider adoption, particularly in response to upcoming EU regulations between 2026 and 2030. The Australian pilot at Rosella Street exemplifies localised efforts to trial these systems. However, as R12 observed, such initiatives remain exceptions rather than the norm, indicating slow diffusion and potential resistance within the Australian construction industry. Respondents agreed that DTs, including AI, BDA, BIM, BCT, IoT, and RFID, can collectively support the development and integration of Digital Marketplaces, MPs, and DPPs. Further respondents indicated a tendency to procure materials directly from manufacturers, viewing guiding platforms as less dependable or efficient in fulfilling project requirements.

Material tracking

Material tracking is becoming crucial in the CE context for effective resource management and optimisation throughout their lifecycle. This approach ensures that materials are sourced, utilised, and disposed of in alignment with CE principles. However, the Australian construction industry faces significant barriers to recycling and material reuse, mainly stemming from inadequate end-of-life (EOL) tracking mechanisms (Oluleye *et al.,* 2023). Addressing this, respondents (R5, R6, R7, R9, and R12) emphasized that effective tracking allows future building owners to access essential data, particularly during the deconstruction phase. This approach allows for real-time monitoring of the materials. It supplies crucial data on their condition, which is frequently overlooked until the building approaches its EOL. R7 and R9 further highlighted that, without DTs, it is challenging to track this information and make informed decisions moving forward, which compromises environmental accountability. Furthermore, R16 emphasized that a closed-loop system depends on the commitment of both buyers and sellers, via take-back schemes or recycling. This commitment is underpinned by DTs such as BCT, IoT, and RFID, which enable effective tracking of materials and products. While all respondents recognised the importance of material tracking within the CE context, some were unfamiliar with the specific technologies available to support it. However, R5 noted that there are ongoing discussions about the effectiveness of tracking technologies in overseeing the long-term lifecycle of materials within a circular economy.

Improving the selection and flow of material

The circular economy maximises material flow and resource efficiency while minimising waste (Ellen MacArthur Foundation, 2012), which can be achieved by optimising the selection, sourcing, and utilisation of materials in construction, manufacturing, and other production processes. R4 and R5 emphasized that design and material handling are key in a CE, requiring innovative approaches for effective management. Digitalisation supports closed material loops here by providing precise resource information (Antikainen, Uusitalo and Kivikytö-Reponen, 2018). For instance, R3 noted that DTs facilitate provenance tracking and lifecycle management, allowing materials to be reintegrated into the CE at the end of their life. Furthermore, R12 highlighted the potential of Material Flow Analysis (MFA) as a systematic approach to monitor circularity across a building's lifecycle. Nevertheless, applying

MFA in practice is constrained by the lack of standardised visualisation tools and spatial geometries, which Munaro and Tavares (2023) recognise as major technical obstacles. Thus, the industry suffers from a dearth of material alternatives (Ababio and Lu, 2023). Technologies like AI, GIS, BCT, IoT, D/Twin, and RFID provide real-time resource flow insights; their effectiveness depends on resolving standardisation challenges and achieving interoperability. Respondents noted that systemic and financial limitations restrict the effectiveness of MFA in promoting circularity in construction.

Aid in gathering, storing, and analysing data Although construction project data is essential for supporting CE practices, collecting, storing, and analysing this data poses significant challenges. Munaro and Tavares (2023) highlight that the lack of effective data management systems significantly impedes circularity initiatives, a concern also emphasized by R7, who points out the inefficiency of using mental or paper-based data storage. This reliance complicates decision-making and raises the risk of data loss and inconsistencies. In contrast, DTs enable proactive risk detection and real-time data analysis for improved site impact management, as noted by R15. The ability of DTs to capture and share data throughout a building's lifecycle (Charef, 2024) presents an ideal framework to support CE goals. R7 further emphasized that comprehensive data capture enables stakeholders to make more informed decisions about costs, carbon reduction, and material reuse. Despite implementation challenges, R14 notes current databases suffer from limited openness, access, and unreliable predictions, reducing their usefulness. This illustrates a broader systemic problem in which data silos and inconsistent standards hinder the ability of Data Trusts to promote circularity. Additionally, although respondents recognised BIM, AI, cloud computing, and big data analytics as helpful in managing data, concerns persist regarding their integration and scalability in industry applications.

Reducing material usage in building structures

Minimising material use in building structures is essential for advancing CE practices, focusing on enhancing manufacturing and design efficiency by tightening resource loops (Talla and McIlwaine, 2024). R1 highlighted that DTs can significantly reduce material use to the minimum required for a building, while R8 emphasized their ability to predict material needs, quantities and timing, thus enhancing inventory management. Additionally, R8 stated that integrating DTs supports assessing materials like used timber for potential reuse in future projects. They can help identify whether certain project elements can be retrofitted instead of discarded, thereby reducing waste and encouraging material reuse. DTs such as AM, AI, and BIM can be utilised to optimise building design, reducing material usage in building structures. However, the use of decreasing materials in construction remains a debated topic within the industry. While respondents acknowledged its theoretical value for promoting circularity, they were hesitant to adopt it in practice due to concerns about compromising the quality of outcomes.

Facilitating a second life for materials

Reusing and repurposing materials to extend their lifecycle is a core principle of the CE, aimed at reducing resource extraction, environmental impact, and waste generation (Ellen MacArthur Foundation, 2012). DTs offer promising support, but their impact is limited by several challenges. R1 emphasized that DTs have the potential to develop comprehensive databases of material properties, theoretically enabling improved reuse decisions. Pilot initiatives, such as the Legacy Living Lab (L3) in Western Australia, showcase how the use of reused components and recyclable materials can substantially reduce waste and embodied carbon (Minunno *et al.,* 2018). This facilitates the identification of effective repurposing or reuse strategies once materials reach the EOL. For instance, BIM models provide detailed information about a building's structure, materials, and components, essential for creating a disassembly plan. In addition to structural data, BIM can store videos, manuals, and visual resources to guide demolition teams in safely dismantling the building and recovering valuable materials. Other than BIM, DTs such as AM, AI, BDA, BCT and IoT can facilitate material reuse and recycling. Nonetheless, such cases remain rare due to limited data infrastructure and incentives in most construction projects.

Advancing Repair

Monitoring the state of buildings enables timely and coordinated maintenance and repair operations, thereby extending their lifespan and reducing the flow of materials through the loop (Tsui, Wuyts, and Berghe, 2024). However, the primary focus in construction is on retrofitting and redesigning buildings, with a strong emphasis on recycling and repurposing materials. R8 emphasized that the importance of repair in CE practices is frequently neglected in the Australian construction industry. Additionally, R8 mentioned that DTs have a considerable opportunity to investigate and incorporate reparative practices within the next five to ten years, offering a more sustainable construction approach and supporting the broader objectives of circularity. DTs, such as D/Twin and IoT, enable real-time management through continuous monitoring and predictive analysis, while BIM supports precise repair planning and AI facilitates data-driven repair decisions. According to the respondents, DTs enable more accurate and timely repairs, which help reduce construction waste and extend the lifespan of buildings. However, the practice of undertaking such repairs remains relatively uncommon in the Australian construction industry.

Material identification and sorting

It is essential to identify and sort out various materials used in construction, typically during demolition, renovation, or at EOL. This is a crucial practice for promoting circularity and reducing waste in the industry. However, reusing and recycling practices in the industry are currently hindered by insufficient waste material segregation and surveillance facilities (Oluleye *et al.,* 2023). Additionally, the sector lacks comprehensive tools for identifying, classifying, and verifying recovered or reclaimed materials (Osei-Tutu *et al.,* 2023). Thus, a significant obstacle to material reuse and recycling is managing complex materials, often composed of a mix of ingredients from demolition projects. R8 claimed that if DTs are adequately implemented to identify and sort materials, they could help the industry transition from costly recycling options to reuse. AI algorithms can be trained on extensive datasets of waste samples to find patterns, predict the characteristics and composition of different waste types, and enhance sorting and disposal processes (Rodrigo *et al.,* 2023). Respondents are aware of the emergence of material identification and sorting mechanisms; however, the industry still lacks effective implementation due to limited technological adoption and insufficient regulatory support.

CONCLUSIONS

DTs are critical for implementing CE practices in the construction sector. However, their adoption remains low in the Australian construction industry due to professionals' resistance to change. According to DOI theory, perceptions lead to the decision to adopt or reject an innovation. Thus, this research investigates how professionals in the Australian construction and CE sectors perceive the role of DTs in enabling circular practices. The findings highlight that technologies like AM, BIM, D/Twins, AI, GIS, BCT, IoT, RFID, and IoT hold significant potential to advance CE practices through design optimisation, advanced repair, material tracking, reuse, real-time monitoring, lifecycle monitoring, standardising MFA, Their current application remains limited due to a lack of awareness, low utilisation, reluctance, scalability challenges, insufficient data infrastructure and incentives, and inadequate regulatory support. This underscores the need for broader adoption and integration to realise the benefits of CE practices in construction fully. Comparing these roles to CE barriers, the study shows how DTs can address issues like material inefficiency, limited reuse, and poor data integration. It offers policymakers evidence-based recommendations to support informed decisions promoting DTs in construction. As a qualitative study, the findings offer in-depth insights, but they do not include statistical evidence that would allow for broader generalisation or comparison. A valuable future study could involve a quantitative investigation assessing the adoption level and impact of specific DTs commercial construction projects.

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