Chapter 17
Driving the Built Environment Twin Transition: Synergising Circular Economy and Digital Tools

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Abstract This chapter offers a comprehensive analysis of the intersection between digitalisation and the circular economy (CE) within the construction sector. It underscores the transformative potential of integrating digital tools to advance circularity objectives across managerial, environmental, economic, and social dimensions. The

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chapter discusses fourteen digital tools and technologies, which play a pivotal role in CE by streamlining data integration and visualisation, enhancing the accuracy of Life Cycle Costing (LCC) and Life Cycle Analysis (LCA) assessments, and supporting the adoption of CE strategies. Moreover, it explores how digital tools can facilitate collaboration among stakeholders, fostering knowledge sharing and effective communication throughout the project lifecycle. Nevertheless, challenges such as the absence of standardised methods, data interoperability issues, and the need for well-defined system boundaries remain. The chapter highlights the critical role of digitalisation in advancing the transition towards CE in the construction sector, emphasising the necessity of overcoming technical and systemic obstacles to fully harness the potential of digital tools in implementing CE. This transition aligns with the broader ambitions of the European Green Deal and the EU Digital Strategy, aiming to create a more sustainable, efficient, and resilient construction industry. By addressing these challenges and leveraging digitalisation, the construction sector can make a significant contribution to a sustainable and circular economy, ultimately benefiting both the environment and society.

Keywords Digitalisation · Circular economy · Digital tools · Key enabling technologies · Twin transition

17.1 Introduction

17.1.1 The Twin Transition—Green and Digital

The European Green Deal initiated the green transition within its sustainable growth agenda, with the aim of reframing the challenge of climate change into a unique opportunity. As stated by the European Commission, this green transition is pivotal for two primary objectives: firstly, to mitigate the consequences of climate change and environmental degradation, and secondly, to strengthen the European Union's (EU) energy self-sufficiency. At the heart of the European Green Deal's roadmap lies the Circular Economy (CE), a critical policy area intended to champion the efficient use of resources and stimulate sustainable economic growth, with a particular focus on the seven most resource-intensive sectors, including construction and building [1].

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Simultaneously, Industry 4.0 presents another essential transition in line with its objectives, referring to the profound changes in the design, production, operation, and servicing of manufacturing systems and products, marking the world's fourth industrial revolution [2]. Known as digital transition, this transformation hinges on several innovative technological advancements:

- **Information and communication technology (ICT)** to digitalise and seamlessly integrate information across the product life cycle and various sources, including different actors and companies.
- **Cyber-physical systems**, encompassing sensors and robots, which support additive manufacturing.
- **Network communications** linking devices, products, systems, and individuals.
- **Simulation**, modelling and virtualisation techniques.
- **Data collection**, big data analysis, and cloud computing.
- **Support human workers**, incorporating robots, augmented reality, and intelligent tools.

The Industry 4.0-driven digital transition offers significant growth potential for Europe across two principal dimensions: firstly, through the adoption of innovative solutions by businesses and citizens, and secondly, by enhancing the accessibility and efficiency of both private and public services. As outlined in the EU's digital transition plan, this transformation opens up *new opportunities for businesses, encourage the development of trustworthy technology, foster an open and democratic society, enable a vibrant and sustainable economy, help fight climate change and achieve the green transition* [3].

Furthermore, following Industry 4.0, Industry 5.0 is a new technological revolution that aims to enhance the transformation of the industrial sector into intelligent spaces based on the Internet of Things and cognitive computing. It is human-centric, sustainable, and resilient and relies on putting artificial intelligence at the service of people, bringing machines and humans together. The main difference between these two concepts lies in the role technology plays in each. In Industry 4.0, it is humans who monopolise the generation of knowledge and intelligence, using technology only as a support mechanism. However, in Industry 5.0, machines take on a different role, becoming the ones who also generate knowledge and intelligence, using artificial intelligence to be at the service of people. The main benefits of industry 5.0 are [4]:

- Reduce cost due to resource efficiency
- Empowered workers remaining in control
- Improved safety and well-being
- Competitive edge in new markets
- Adapted training for evolving skills
- Competitive industry by attracting best talent
- A solution provider for people and for our planet

The EU aspires to become a sustainable and competitive economy. To realise this vision, it is imperative for the European construction industry to embrace the practices

of Industry 4.0 and CE, given their profound impact on the economy [5], environment and social communities. These two paradigms hold the potential to revolutionise the construction sector, enabling more sustainable and efficient practices that support the dual green and digital transitions. This is particularly critical because the construction industry stands as one of the largest consumers of raw materials and energy while concurrently generating a significant volume of waste and emissions [6].

The concept of twin transition, encompassing green and digital shifts, has been presented by the EU as the cornerstone of the transformations that will define the EU's future. This twin transition, propelled by a top-down approach and holding a prominent place on the political agenda, signifies the transformation necessary to attain green and digital objectives. The synergy arising from the amalgamation of both transitions goes well beyond their individual impacts. Digitalisation can amplify the green transition, and it is indispensable in comprehending, evaluating, and comparing alternatives, thereby challenging the prevailing business-as-usual (BaU) approach and charting new paths towards a more sustainable, circular, and digital future, spanning the three core dimensions of sustainable development: social, economic and environmental.

Aligned with the European Green Deal and the EU Digital Strategy several research projects have been supported by the EU, namely the GREEN AT YOU project from the EntreComp Community, an initiative that focuses on addressing the challenges and opportunities associated with the green and digital transition in Europe, aiming to make green job opportunities more inclusive and accessible to people in vulnerable situations, supporting the European Commission's agenda for a cleaner environment, green economy, and digitalisation, aligning with this twin transition [7].

For a successful twin transition, the Strategic Foresight Report [8] has identified ten key areas of action, including:

1. Strengthening resilience and open strategic autonomy in critical sectors.
2. Stepping up green and digital diplomacy.
3. Strategically managing the supply of critical materials and commodities.
4. Strengthening economic and social cohesion.
5. Adapting education and training systems.
6. Mobilising additional future-proof investment into new technologies and infrastructures.
7. Developing monitoring frameworks.
8. Ensuring a future-proof regulatory framework for the Single Market.
9. Stepping up a global approach to standard-setting.
10. Promoting robust cybersecurity and secure data-sharing framework.

In the "Towards a Green and Digital Future" report [9], the key requirements for the twin transition are grouped into five thematic clusters:

1. **Social**, to ensure a just transition, increase societal engagement in the change, and ensure privacy and ethical technology use.

2. **Technological**, implementing innovation infrastructure, building a technology ecosystem, and ensuring data availability and security.
3. **Environmental**, avoiding rebound effects, and reducing the impact of green-digital technologies.
4. **Economic**, to create enabling markets, ensure diversity of market players, and equip labour with relevant skills.
5. **Political**, implementing adequate standards, ensuring policy coherence, and channelling investment into green-digital solutions.

This study underscores the significance of the buildings and construction sector in the green transition. Within an industry characterised by lower and relatively stagnant productivity compared to other manufacturing sectors and a shortage of skilled labour, the digitalisation and industrialisation of the construction process provide an opportunity to address both challenges. This can be achieved by reducing dependence on labour and increasing productivity.

17.1.2 Key Enabling Technologies (KETs)

Key enabling technologies (KETs) represent the catalyst for rapid and far-reaching technological advances that reshape our economy, ushering in new markets and stakeholders [10]. Aligned with the objective of addressing paramount societal concerns, including the environment, energy, mobility, health and well-being, food and nutrition, security, privacy, inclusion, and equality, the European Commission champions six KETs organised into three primary domains:

1. Production technologies:
   - Advanced manufacturing
   - Advanced materials
   - Life-science technologies
2. Digital technologies:
   - Micro/nano-electronics and photonics
   - Artificial intelligence
3. Cyber technologies
   - Security and connectivity

A subset of these KETs is intimately intertwined with digitalisation technologies within the construction sector, which will be expounded upon in subsequent sections.

The analytical report from the European Construction Sector Observatory [11] entitled "Digitalisation in the Construction Sector," presents an overview of the most pertinent digital technologies in the construction sector, categorised into three distinct areas:

- Data acquisition: sensors, Internet of Things (IoT), and 3D scanning.
- Automating processes: robotics, 3D printing and drones; and
- Digital information and analysis: Building Information Modelling (BIM), Virtual/Augmented Reality (VR and AR), Artificial Intelligence (AI), and Digital Twins (DT).

Governments have exhibited robust support for the digitalisation of the Architecture, Engineering, and Construction (AEC) industry, resulting in an encouraging acceleration. This momentum is underpinned by a confluence of factors, including political priorities and financial backing, the imperative to enhance productivity while reducing costs, and the market demand for digital technologies. Nevertheless, several main challenges must be overcome, notably the scarcity of skilled labour and awareness, as well as the expenses associated with equipment and software.

The most relevant digitalisation technologies in the construction sector are elaborated in the European Commission's report "Supporting Digitalisation of the Construction Sector and SMEs: Including Building Information Modelling" [12]. Key technologies outlined in this document encompass Building Information Modelling (BIM), Additive Manufacturing, Robotisation, Drones, 3D Scanning, Sensors, and IoT. Within this document, BIM is not merely regarded as a technology but as a comprehensive methodology that underpins and harmonises the entire suite of digital advancements.

17.2 Analysis of Existing Key Enabling Digital Technologies for the Construction Sector

Within the realm of circular built environments, digital technologies and transformations have emerged as vital enablers in closing, slowing, and narrowing material loops. Aligning circular and digital transitions is believed to bring multiple benefits to environment, economy and society. In this regard, numerous studies have explored the best practices for implementing CE in the construction sector through digitalisation, shedding light on several tools, innovative products, applications, and services that have demonstrated significant benefits. Together, they create a dynamic ecosystem of digital technologies that fuel socio-economic transformation [13]. This chapter specifically highlights 14 key enabling digital technologies that play a pivotal role as drivers for the digital CE within the built environment.

17.2.1 Building Information Modelling (BIM)

Building Information Modelling or Building Information Management (BIM) is a methodological approach that revolves around creating a parametric 3D virtual model, or multiple linked models, to consolidate information about a building. This

process begins in the early stages, such as commissioning or conceptual design, and ideally extends throughout the entire life cycle of the structure. The BIM model starts by representing existing conditions (the existing building or site), serves as a tool during the design phase to centralise and coordinate various aspects like architecture, engineering, and landscaping, and continues to be a valuable resource during construction, offering support for construction management and design modifications. This evolving model, often referred to as an "as-built BIM model", remains relevant after being delivered to the client or facility management team, supporting use and maintenance activities. Ultimately, it is ideally employed in the end-of-life (EoL) phase, assisting with demolition or, preferably, dismantlement and waste management. Throughout the building's life cycle, the BIM model enables various analyses, such as energy efficiency, material usage, layout planning, and sun exposure, providing data for various alternative scenarios and informing decision-making [14].

The BIM methodological approach hinges on data exchange and digital information interoperability. This entails seamless data sharing among different stakeholders with minimal or no information loss. The concept of "Open BIM" in contrast to proprietary software and data formats, is championed by the international organisation BuildingSMART, which promotes data exchange [15]. BuildingSMART is an international organisation dedicated to advancing research and knowledge in developing interoperable, open, and international BIM standards. Industry Foundation Classes (IFC) stands out as the widely accepted standard governing how building information is communicated and shared among stakeholders and applications using a Common Data Environment (CDE). A CDE is a common digital space that hosts the relevant information for collaboration, exchange, and communication to deliver a project, and comprises two components: the Data Standard (what is the information required and how the information is structured for sharing and collaboration within a common data environment to deliver a project) and the Data Platform (the computer system or technology platform that the data and information is stored, shared and collaborated on in a CDE) [16].

The BIM model can be developed with various levels of detail or level of development (LoD). It starts at LoD 100 with only basic graphical data and may progress to LoD 500, which includes detailed graphical and non-graphical data and information, as follows:

- LOD 100, Conceptual Design: At this level, the focus is on the physical appearance and visual or conceptual design, accounting for approximately 20% of the total data.
- LOD 200, Approximate Geometry: This level involves basic or schematic representations with parameterised dimensional information, constituting about 40% of the total information.
- LOD 300, Precise Geometry: Here, the model includes specific functions in addition to geometric dimensions, making up roughly 60% of the total information.

- LOD 400, Fabrication: This level encompasses the parameters necessary for a particular model and is typically considered at the contracting or construction project level, representing around 80% of the total information.
- LOD 500, "As Built": This level refers to a highly detailed model that closely replicates the actual building as constructed, comprising 100% of the total information.

The European standard ISO 19650-1 substitutes this LOD definition (more commonly used in the USA) by Level of Information (LoI) needed. In the UK the different levels of LoI are more granular and related with different project stages, according the exchange information requirements (EIR), that includes the technical aspects (such as details of software platforms, definitions of levels of detail etc.), management aspects (such as details of management processes to be adopted in connection with BIM on a project); and commercial aspects (such as details of BIM Model deliverables, timing of data exchange and definitions of information purpose) [17]. By using these different LoD levels, BIM models can cater to a range of project phases and requirements, from initial concepts to the faithful representation of the final built structure.

BIM models are often associated with various dimensions. The journey begins in a pre-BIM stage with a 3D model, and additional dimensions include the 4th dimension, time, introduced through project planning; the 5th dimension, cost, for estimating and cost control; the 6th dimension, sustainability, focusing on impacts and energy estimation; and the 7th dimension, utilisation, aligned with facility management (FM). The concept of nD extends to consider additional dimensions, with the eighth dimension potentially connected to circularity and EoL activities [18]. Presently, these dimensions are often referenced as BIM model functionalities or uses. Figure 17.1 illustrates the established BIM dimensions and their respective applications.

According to MacLeamy curve [19], incorporating BIM into the building design and construction process shifts the primary effort from the construction phase, where most effort traditionally occurs, to an earlier stage during design. This phase is critical because it offers the highest potential for influencing overall costs and functional

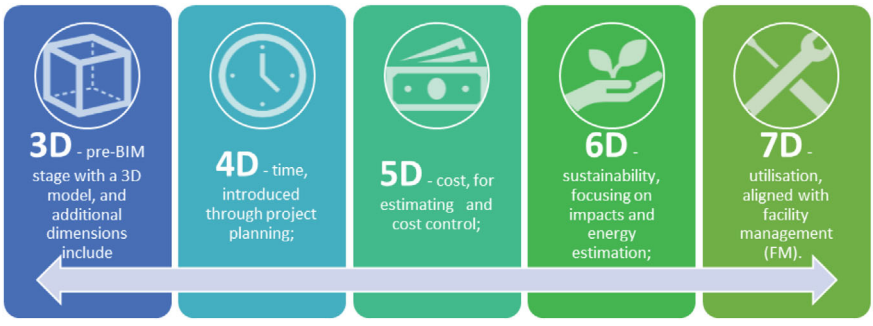

Fig. 17.1 3D to 7D dimensions of BIM

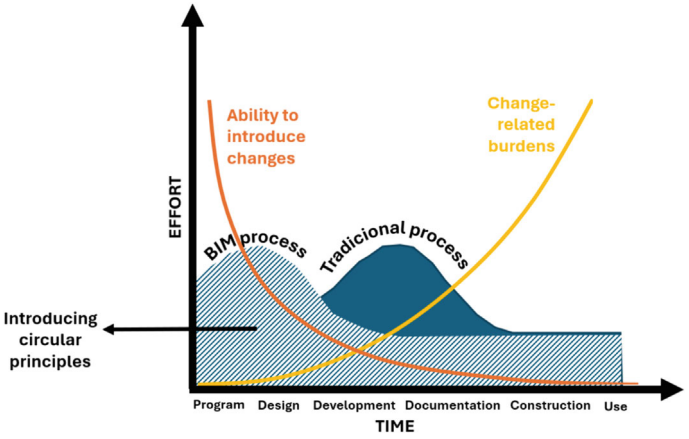

Fig. 17.2 Time versus effort along the building's life cycle: incorporating BIM use (based on MacLeamy curve) and adopting circular principles

capabilities while keeping the cost of potential future changes relatively low. Therefore, adopting BIM at an early design stage can leverage the adoption of circularity strategies such as design for adaptability and design for disassembly with minimal or no associated costs. This underscores the importance of embracing BIM in design and introducing circularity principles at an early stage when change-related burdens are relatively low, while maintaining the ability to introduce change in later lifecycle stages remains high, as depicted in Fig. 17.2.

17.2.2 Digital Twin

A digital twin (DT) represents a virtual model of a real-world product or building which consists of the actual geometry, structure and physical characteristics [20]. A DT can also be referred to as a 3D digital copy of a real-world physical asset [21].

During the construction phase, the BIM model (previously developed during design and preparation phases) should be constantly updated in a so-called "as-built BIM". After the conclusion of the works, the final BIM model becomes a digital twin, representing the physical asset and playing an important role in managing the real building.

DTs are distinguished by the smooth integration of the cyber and physical spaces as well as virtual data throughout a product or building lifecycle [22]. They find application in several areas such as product design, production planning and assembly [22]. In the built environment, having a DT of a real-world asset would allow tracking aspects like energy management, indoor comfort, and safety [23]. Besides enabling the monitoring of the current state, it facilitates predicting future state,

allowing proactive measures for optimal operation [24]. Considering these capabilities, DTs are instrumental in assessing building performance and alternatives, supporting optimisation analysis, and enhancing reliability opportunities [25].

In the context of circularity, DTs are essential as they consist of information about the built-in materials of a building, which is relevant for implementing circularity practices [26]. When combined with Material Passports, DTs can help extend the lifetime of building elements through predictive maintenance [27] and facilitate the reuse of materials and elements at the end-of-life stage [28].

17.2.3 Additive Manufacturing (3D Printing)

Additive manufacturing, commonly referred to as 3D printing, has emerged as a transformative force in various industries, offering a multitude of benefits. Unlike conventional manufacturing methods that involve subtracting material from a larger piece to create parts and products, additive manufacturing stands out for its ability to reduce waste in production processes, promote decentralised manufacturing, and facilitate increased repair and remanufacturing. The primary value drivers of 3D printing encompass simplified manufacturing processes, swift prototyping, innovative design capabilities, product customisation, use of recycled materials, less waste generation, on-demand production, spare parts availability, and cost efficiency [29, 30].

The applications of additive manufacturing span diverse sectors. In the realm of manufacturing and industry, it is employed for rapid prototyping and has gradually expanded into full-scale production, thereby reducing lead times and development costs for prototypes [31]. In the medical field, 3D printing has revolutionised the production of medical devices, prosthetics, implants, and even the bioprinting of human tissue and organs [31]. The construction industry has also embraced additive manufacturing for tasks such as concrete printing and the fabrication of building components from metals and polymers. This enables resource optimisation, waste reduction, the creation of lightweight structures, and the use of recycled materials. Furthermore, additive manufacturing has made significant contributions to the automotive and aerospace sectors, exemplified by Boeing's use of 3D printing to produce over 50,000 units of more than 900 distinct parts [13]. Other industries benefiting from additive manufacturing include jewellery, where intricate and personalised designs are made possible, as well as the food industry, where advancements in 3D printing technology enable the creation of unique shapes and designs.

In the OECD Digital Economy Outlook, 3D printing is recognised as an application empowered by AI, big data, and simulations [32]. Digitalisation in additive manufacturing provides a range of advantages and plays a pivotal role in advancing circular construction practices as outlined by Antikainen, Uusitalo and Kivikytö-Reponen [33].

Firstly, digital additive manufacturing enables design optimisation through the use of advanced software tools, such as parametric modelling (e.g., BIM) and generative

design algorithms. Architects and designers can create intricate, customised shapes that maximise material efficiency and minimise waste. Additive manufacturing techniques, like 3D printing, can then directly translate these optimised designs into physical structures.

Secondly, digitalisation promotes material efficiency by facilitating the precise layer-by-layer deposition of advanced materials and composites. This precision reduces waste during the construction process. Additionally, digitalisation allows for the analysis of material properties and performance, ensuring the selection of suitable materials for specific building components.

Another important role of digital additive manufacturing is on-demand manufacturing. This implies that building components are produced only when required, reducing the need for excess inventory and minimising waste. Furthermore, producing components in close proximity to the construction site reduces transportation costs and the carbon emissions associated with traditional supply chains.

Modularity and customisation are also encouraged through additive manufacturing and digitalisation. Modular building components can be easily assembled and disassembled, promoting the reusability and recyclability of materials. Digitalisation plays a vital role in designing and coordinating these modular systems, ensuring compatibility and efficient assembly.

Reduced energy consumption is another benefit of digitalisation and additive manufacturing. By optimising designs, reducing material waste, and enabling on-demand manufacturing, the overall energy required for construction can be minimised. Additionally, additive manufacturing techniques can incorporate energy-efficient features, such as complex geometries for natural ventilation or the integration of insulation materials [30].

17.2.4 Blockchain Technology (BCT)

Blockchain is a geographically dispersed and shared database, known as a distributed ledger. It operates within a peer-to-peer network, employing a consensus mechanism to maintain the integrity and accuracy of data, allowing for replication across computer nodes (participants). Consequently, any information exchanged between participants remains confidential, transparent, and auditable [34].

As a decentralised and transparent system designed to accommodate a vast and continually expanding volume of data, BCT holds considerable potential for applications in the built environment. Specifically, it can facilitate sustainable development and accelerate the transition to a CE, support data-driven decision-making across all stages of a product's life cycle and address the productivity challenges typical of the construction sector. Consequently, over the past decade, it has garnered significant attention from scholars. Nonetheless, the full adoption and broader application of BCT concepts remain limited, with the majority of research existing in the conceptual domain, complemented by only a few pilot studies such as the life cycle of HVAC [35] and additive manufacturing [36].

Thus far, the academic consensus primarily revolves around two key points. Firstly, the potential applications of BCT offer numerous advantages, including the design of mechanisms to incentivise environmentally friendly behaviour, increasing system efficiency and transparency throughout the entire product life cycle, reducing capital and operational costs, and promoting sustainability performance monitoring and reporting within supply chain networks [37]. Secondly, the use of BCT as a standalone tool in a circular built environment is seldom recommended. Instead, it is often suggested in conjunction with other digital technologies, such as the IoT [38, 39], Big Data Analytics [39], BIM [40], Digital Twins (DT) [38], Material Passports [41, 42] and additive manufacturing [36]. One of the earliest concepts introduced involved the integration of IoT, big data analytics, and BCT to conduct life-cycle assessments in energy savings, ecosystem quality management, and waste management [39].

A limited number of studies utilising BCT as a standalone tool have concentrated on enhancing waste management systems. In these studies, BCT was employed to optimise the system and foster greater trust between citizens and waste management operators. Two frameworks were introduced for this purpose: the first was focused on the management of urban waste streams in its entirety [43], while the second was concentrated on construction waste exclusively [44]. Both systems have the potential to enable the tracking and verification of significant data sets, including but not limited to the volume of waste generated or treated and associated rewards. These data are generated by various stakeholders within waste management systems.

Other frameworks explore the integration of BCT with BIM [40] and with DT [38]. The first framework promotes the CE by encouraging collaboration between stakeholders, sharing information about building components and materials, and developing repositories of reusable BIM families while motivating designers to utilise them. The second framework integrates IoT, BIM, and DT throughout the various phases of a project's life cycle. During the design phase of the Decentralised DT Cycle, 3D BIM data and design parameters are stored on the BC, while 4D BIM and procurement data are retained during the construction phase, and 6D BIM and IoT data are maintained during the operational phase.

17.2.5 Scanning Technologies

Scanning technologies, commonly known as laser scanning or Light Detection and Ranging (LiDAR), are advanced systems designed to determine the distances to various points surrounding a laser scanner by measuring the time it takes for a light pulse to travel to and from an object [45]. These technologies primarily provide local coordinates, which are subsequently cross-referenced with known geographic coordinates of objects. Laser scanners can be either static (terrestrial, positioned on the ground) or mobile (portable, mounted on drones, aircraft, or vehicles) and are capable of collecting vast amounts of data, necessitating intensive pre-processing before further applications.

In the realm of the built environment, scanning technologies are predominantly employed for purposes such as inspection, site monitoring, and 3D reconstruction [46]. Their application contributes significantly to enhancing circularity within the built environment by facilitating the 3D reconstruction of objects and the creation of BIMs and City Information Models (CIMs). These models are enriched with valuable information, enabling them to support local governance and various smart city and CE initiatives [47].

The academic literature on laser scanning technologies, in the context of their support for the CE, varies in terms of the scanning area and the level of detail (LoD). For instance, LoD 1 entails representing a building with basic information such as its footprint area, height, and flat roof, while LoD 2 includes a more precise representation that accounts for roof slopes. As a general rule, the larger the scanning area, the lower the level of detail.

Laser scanning technology has been applied across a wide range of projects, from assessing the geometry for single buildings in Vienna [48] to scanning 1,361 buildings in Hong Kong [47]. It has also been employed for projecting mineral Construction and Demolition Waste (CDW) flows [49] and conducting life cycle assessments for entire cities in Luxembourg [50]. Recent advancements in this field include the development of a methodological framework for semi-automated reconstruction at higher levels of detail for existing buildings, aimed at creating CE passports [51]. Another notable initiative involves the reconstruction of building facades to facilitate energy-based simulations for retrofitting existing structures [52]. These applications highlight the versatility and significance of scanning technologies, not only in improving circularity but also in advancing sustainable practices in the built environment.

In addition to providing information about the geometry and surface materials, laser scanning is employed to facilitate circularity practices such as preservation, reuse, and recycling. However, for a comprehensive understanding of building elements' material composition, it becomes essential to delve beyond surface materials. Addressing this need, a study by Honic et al. [53] used Ground Penetrating Radar (GPR) to identify material types within walls and slabs, generating Material Passports (MPs) for a building. GPR, a near-surface geophysical tool, allows non-destructive characterisation of shallow subsurface targets by detecting changes in the electromagnetic properties of materials [54]. Its non-destructive nature has been extensively applied in archaeological studies over the past decades. In the context of CE and the built environment, GPR holds significant promise for detecting built-in materials without causing damage. This capability aligns with the circularity principles of preservation, reuse, and recycling, making GPR a valuable tool for sustainable practices in construction and material management.

17.2.6 Internet of Things (IoT)

The Internet of Things (IoT) can be described as a networked system of sensors and actuators integrated with a computing system, enabling internet connectivity among

sensor-equipped devices for autonomous data collection and analysis [55]. This technology facilitates the monitoring and management of the health and activities of interconnected objects and machines.

In the context of CE, IoT has the potential to revolutionise various industries, including construction, services, manufacturing, logistics, and supply chains [55]. It facilitates stakeholder connection throughout the value chain by leveraging sensor-collected data [56]. By enabling autonomous data collection and analysis, IoT helps reduce waste, losses, and expenses, while also enhancing the tracking and traceability of materials throughout the supply chain [29], thus supporting the implementation of CE principles [56]. In urban environments, the concept of smart cities exemplifies how IoT contributes to CE improvement by enabling data gathering and interpretation for sustainable solutions, efficiency enhancement, pollution reduction, and promotion of eco-friendly consumption [57].

Reuter [58] highlights the transformative potential of IoT within CE by facilitating digitalisation and optimisation of systems through measurements and quantification tools. Moreover, IoT enables CE models to incorporate dynamic feedback control loops, connecting all system stakeholders and allowing for the assessment of the impact of actions taken by different actors throughout the lifecycle of physical products [56]. Real-time data and information provided by IoT can lead to the optimisation of products, goods, services, and policy formulation, resulting in a significant reduction in the environmental footprint of the CE systems.

The digitisation of the CE information through IoT brings about transformative changes in business models and the introduction of CE-based marketing strategies. This partnership aims to establish a business and consumption model rooted in social responsibility, reduced consumption, and efficient management of product life cycles, with a strong emphasis on reuse, recycling, and reduction. Transitioning from the traditional marketing mix to the green marketing mix is considered a profitable and sustainable management process and a key business strategy of the future [59]. As argued by McDaniel and Rylander [60], green marketing has become a crucial factor in the mission, vision, and values of companies. Furthermore, the implementation of the circular and digital economy model relies on the effective utilisation of the 4Ps (price, product, placement, and promotion), with IoT playing a significant role in this process. In this regard, IoT provides the necessary support for companies to achieve a CE with long-term effects. For instance, LCA is one area where IoT's impact is evident, as it is a widely used method for quantifying sustainability within organisations [59].

The transition to a CE with the assistance of IoT is significantly influenced by the supply–demand relationship. The market's responsiveness to consumer preferences is a driving force behind the digitisation of production and consumption processes. This integration has the potential to enhance productivity and sustainability in both local and global economies, as well as in various business models. IoT and the CE share a common focus on the entire product life cycle, demanding product designs that align with present and future market expectations while adhering to the 17 UN Sustainable Development Goals [59].

17.2.7 Artificial Intelligence (AI)

Artificial Intelligence (AI) is one of the main technologies that can accelerate the transition towards a CE [61]. McKinsey Global Institute [62] estimated that AI could potentially generate a staggering $13 trillion in global economic impact by 2030. The Ellen MacArthur Foundation [63] underscores the transformative power of AI in imbuing inanimate objects with intelligence. Its integration into design, infrastructure, and business models is driving the creation of regenerative systems. This 2019 report identifies several ways in which AI can expedite the transition to a CE:

- Enhancing Problem Solving: Advanced AI enables complex problem-solving in significantly less time, with algorithms trained and applied to real-life challenges throughout the development process.
- Unlocking CE opportunities: AI contributes to more efficient design and optimisation of business models and infrastructure, hastening the establishment of a CE.
- AI can potentially unlock three main CE opportunities: (1) Circular product, material, and component design; (2) Circular business model operations; and (3) Infrastructure optimisation to facilitate the circular flow of materials and products.

A substantial volume of data is generated at various stages of the product development lifecycle, from manufacturing to utilisation and EoL [64]. AI can play a pivotal role in analysing and further enhancing these processes. Furthermore, the integration of circular design tools and methods with AI can significantly enhance product circularity within a business context [65].

AI excels in the analysis of large datasets, saving time through high-performance computing. Despite its dynamic and complex nature with numerous parameters, AI applications in the construction sector offer substantial opportunities. Notable current and actively researched AI applications in construction include: safety measures, automated monitoring of structural health for buildings, bridges, and road pavements, detection of safety risks at construction sites, activity recognition at construction sites, modelling of energy demand for buildings, construction cost prediction, computer vision, intelligent optimisation of scheduling, planning, and design [66–68]. AI technologies are also employed in green buildings for monitoring building health, safety, and risk assessment, sustainability ranking, CDW management, resource optimisation, and lifecycle cost reduction [69].

Future trends in the construction sector include the development of construction robots to reduce workforce dependency and improve efficiency, the utilisation of cloud-based virtual and augmented reality for enhanced inspection and safety, AI of things (AIoT), DT, 4D printing, and BCT [67]. Currently, the main challenges for AI application within the construction sector encompass site management, financial expenses, security concerns, data availability, and the disparity between the accuracy of machine learning algorithms and practical application [66, 68].

Designing construction site layouts remains a challenging problem in construction projects. Spatial and temporal parameters of site layouts are crucial for efficient site management [70, 71]. These parameters include access routes, material storage, material handling methods, administrative buildings, and job equipment. While defining an optimal layout has proven difficult [70], a valuable research direction is to determine an optimal site layout with circularity in mind. Although machine learning has been applied to job site optimisation, the use of satellite images and explanatory visualisation techniques to identify site similarities remains unexplored.

Despite advancements in the CE, deep learning has not seen widespread use in this field, primarily due to the absence of large-scale multimodal datasets. Existing assessments and indexes heavily rely on open datasets available in municipalities, such as material flow data in industrial sectors [72, 73]. This reliance introduces limitations and accuracy issues, particularly for developing and less developed countries.

17.2.8 Big Data Analytics (BDA)

In the past decade, deep learning has emerged as a powerful AI methodology, effectively addressing a wide range of challenges across various domains. These applications include object detection in visual data, automatic speech recognition, neural translation, and tumour segmentation in computer tomography scans. While artificial neural networks (ANNs), the precursor of deep learning, trace their roots back to the 1960s, it was in the 2010s that deep learning systems experienced a remarkable surge in performance. This transformation was facilitated by the availability of graphical processing units for computation and the advent of Big Data Analytics (BDA). This is the process of examining and analysing concealed patterns, correlations, trends, and insights within these vast data collections, with the primary objective of extracting valuable information and knowledge. This information is then utilised to drive data-informed decision-making, enhance business processes, and tackle intricate challenges.

In the field of CE, the application of BDA is seen as a promising methodology for harnessing information gleaned from various systems of record, including sensors and IoT devices. This empowers decision-making capabilities, especially in logistics and supply chain management (SCM), which is pivotal for the successful implementation of CE and the advancement of its comprehensive principles [74]. It's worth noting that Big Data is often treated not as an isolated concept but rather as an analytical approach applied to analyse extensive data originating from diverse sources. Through the integration of comprehensive and lifelong information, Big Data facilitates the implementation of innovative strategies [56].

From the perspective of stakeholders, the adoption of BDA would significantly enhance decision-making across a spectrum of business sectors. However, the existing literature faces a challenge in understanding how BDA contributes to better decision-making, primarily due to a lack of detailed investigation [75]. This can be partially attributed to the varying interpretations of the CE concept among scholars.

For instance, some studies characterise CE as the management of closed loops in linear industrial production [76], while others believe in the spiral-loop system concept as in [77]. According to Tseng et al. [78], the central concept of SCM, the "closing-loops" strategy, has conventionally been employed in linear production systems, typically within a single supply chain and connected with vertically integrated decision-making systems. Nonetheless, this "closing loops" approach is also applicable in industrial and urban symbiosis within multi-supply-chain networks, involving cross-industry decision-making.

17.2.9 Cloud Computing and Applications

Cloud computing is a revolutionary paradigm for managing and utilising both hardware and software resources. It empowers businesses to share various aspects of their information technology infrastructure (IT), including both physical and non-physical components. Integrating an enterprise's IT infrastructure into projects can lead to substantial reductions in initial investment costs [79]. Despite its potential, the construction industry has been hesitant to embrace these new technologies due to high upfront costs, resulting in limited cloud computing applications [80].

The potential benefits of cloud computing technology in construction are numerous:

- Economic Efficiency: It offers economic benefits by decreasing the operational costs for construction companies [79].
- Level Playing Field: It creates a level playing field for small and medium-sized enterprises (SMEs) to compete with larger corporations without significant upfront investments [81].
- Secure Data Storage: It ensures the secure storage of construction data, meeting the required security standards for IT infrastructures [79].
- Remote Data Access: It facilitates remote storage and retrieval of vast construction data without space and time limitations [79].
- Centralised Data Repository: It creates a central repository system for construction data, facilitating stakeholder integration [82].

The impact of cloud computing applications on CE in construction has gained significant recognition [83–85] due to their role in reducing material waste at construction sites, minimising incorrect deliveries, and streamlining file organisation, contributing to cost reduction and improved project timelines [86–88].

Construction sites are inherently hazardous due to their dynamic and complex structures, which increases risks without real-time on-site safety information. However, leveraging cloud technology to provide instant access to safety information can reduce occupational accidents [89, 90]. Sustainability goals are also achievable by managing energy consumption and reducing CO_2 emissions through cloud technologies, which enable the efficient management of building energy information alongside safety data [91]. Timely material supply to construction sites significantly

influences project cost and duration. In this regards, cloud technologies and IoT sensors play critical role in ensuring efficient and timely delivery by monitoring material supply movements [92] and enhancing cooperation and communication among numerous stakeholders [84].

17.2.10 Virtual and Augmented Reality (VR/AR)

Virtual Reality (VR) and Augmented Reality (AR) are two technologies that have the potential to support and enhance the CE. AR technology overlays digital content, including images, videos, and 3D models, onto real-life environments and physical objects, enhancing the user perception of reality by transforming their immediate surroundings into an interactive learning environment with virtual elements [93]. In contrast, VR immerses users in a simulated environment [94], offering a completely virtual experience with diverse applications, including education and training. In the context of the CE, both AR and VR can be employed to provide information and guidance on recycling, waste sorting, sustainable consumption, and to simulate and visualise sustainable practices and processes [93].

Several applications of VR in promoting the CE in the construction sector include the integration of VR and BIM for effective construction planning and enhanced safety. This BIM-based system enables advanced simulation and communication, offering an immersive experience to all project stakeholders. Real-time synchronisation between BIM and VR models allows for automatic updates, streamlining decision-making during construction.

Combining VR with BIM and LCA contributes to the assessment and reduction of carbon footprints in construction projects. During the conceptual design phase, VR and BIM play a pivotal role in generating LCA and cost assessments that assist designers and clients in making well-informed decisions. Experiments have shown that users prefer economical solutions without compromising aesthetics, and their concern for sustainability increases when exposed to LCA data. Moreover, simplified cost and carbon footprint results have been found to influence users' perceptions. This underscores the potential of VR-BIM-LCA integration in making informed decisions regarding material selection and sustainable solutions.

Augmented Reality (AR) technology has the potential to enable environmental designers, urban planners, and other infrastructure development roles within the built environment to help key decision-makers invest in a CE for their city or community. AR can be used to explore CE solutions, enabling key audiences and actors to be engaged in a more active way [95], by fostering their interest perception on CE principles. Additionally, AR can serve as an engagement tool to increase end-users' interest and engagement with CE principles, educating the public about CE and promoting sustainable practices [96].

Moreover, AR technology can be used for disaster training and response. AR mobile applications can effectively engage both citizens and disaster response authorities, thereby enhancing their preparedness and response capabilities. By leveraging

AR technology, disaster training and response efforts can provide immersive, real-life scenario simulations, leading to more effective emergency response [97].

17.2.11 Geographic Information System (GIS)

Geographic Information Systems (GIS) are advanced computer systems designed to collect, store, manipulate, analyse, manage, and map various types of geographically referenced information [98, 99]. Within GIS, data is seamlessly integrated with descriptive information on a map, which aids users in identifying patterns, relationships, and geographical contexts [99]. Notably, GIS combines data with cartographic elements, creating a synergy of spatial attributes and contextual descriptions that greatly enhance the understanding of spatial patterns, relationships, and geographic contexts [100]. The versatility of GIS extends across a broad spectrum of fields and industries, making it an invaluable tool for cartographic production, analytical inquiries, information dissemination, and the resolution of complex challenges.

The literature strongly supports the idea that GIS can play a pivotal role in promoting the adoption of a CE in the built environment. Firstly, GIS solutions actively facilitate circular logistics planning and environmental and economic impact assessments in the built environment [101]. By integrating data related to waste generation, material flows, and resource availability, GIS can effectively identify opportunities to optimise resource utilisation, reduce waste, and encourage circular practices. Secondly, GIS can be employed to map and manage resources in the built environment, including emissions, air pollution, and waste. It is instrumental in identifying and locating sources of reclaimed materials, such as salvaged building components or recycled materials, and streamlining their incorporation into construction projects [48, 98]. Thirdly, GIS can be seamlessly integrated into decision support systems for CE initiatives in the built environment. It offers decision-makers a comprehensive view by combining spatial data with other relevant information, such as economic factors, environmental impacts, and regulatory requirements [101]. This aids in evaluating the feasibility and potential benefits of CE strategies.

Furthermore, GIS can support the monitoring and evaluation of CE initiatives in the built environment. It can track project progress, measure resource efficiency, and assess the environmental and economic impacts of circular practices [48]. GIS also facilitates data sharing and collaboration among stakeholders, enabling better coordination and communication in CE projects. Finally, GIS serves as a valuable tool for engaging stakeholders in CE initiatives. By visualising data and scenarios, GIS effectively communicates the benefits and potential outcomes of circular practices to various stakeholders, promoting awareness, participation, and collaboration [101].

17.2.12 City Information Modelling (CIM)

City Information Modelling (CIM) is a novel concept that encompasses the use of intelligent urban models with high quality geospatial information and an update and comprehensive database [102]. CIM can also be defined as a digital representation of a city that integrates various data sources, including spatial data, infrastructure information, and environmental data [103, 104]. This integration enables the visualisation, analysis, and simulation of urban systems, empowering decision-making processes [102, 105].

The literature presents various interpretations and definitions of the CIM concept. In general, CIM aligns with the use of geospatial information and digital technologies [106]. As presented by Kehmlani [107], one of the early adopters of the acronym, CIM can be likened to BIM but specifically applied to urban environments. In this regard, intelligent city models should closely resemble intelligent building and infrastructure models, providing comprehensive information to simulate various aspects of cities, such as traffic flows, energy use, and natural disaster impacts [107]. Stojanovski et al. [108] propose that the CIM concept blends elements of GIS, Computer-Aided Design (CAD), and BIM, forming the basis for digital tools to plan and design smart cities. Xu et al. [109] state that CIM is inspired by BIM and should include all aspects of city information, establishing the integration of BIM and GIS, where building information is provided through BIM and external information is provided by GIS. Almeida and Andrade [110] perceive CIM as an intelligent computational model that incorporates processes, policies, and technologies, facilitating collaboration among various stakeholders to develop sustainable, participatory, and competitive cities. Dall'O' et al. [111] consider CIM the "latest advancement of BIM" and highlight its potential for analysing city components and creating richly informative 3D models. They also emphasise the benefits of using CIM for decision-making, management, monitoring, control, and maintenance in the energy sector. Thompson et al. [112] discuss the planning of future cities and consider CIM as the practical application of the digital processes for the management and planning of cities, involving the active participation of citizens and stakeholders. Sirakova [113] proposes that the CIM model can be seen as a continuous process of development and renewal, mirroring how cities evolve like living organisms. Wang and Tian [114] define CIM as an organic synthesis of 3D models and urban information, integrating BIM, GIS, IoT, and other technologies. According to the authors, CIM exhibits four main characteristics: multidimensionality, visualisation, openness, and perception. Based on their findings, city information models should be based on the integration of data across various spatial scales, emphasising the importance of BIM, GIS, and IoT as key technologies for CIM.

While a consensus on the CIM concept is lacking, the literature indicates an understanding of its equivalence to the BIM concept, but with a focus on urban environments, and a tendency to associate CIM with the integration of BIM and GIS. Although not universally embraced by urban planners, researchers, and the software

industry, it is noteworthy that CIM has garnered increased attention, evidenced by the growing body of research published on the topic in recent years.

17.2.13 Digital Platforms and Market Places

An online or virtual platform is a digital service based on a software system that operates via the internet, facilitating interactions among and between independent users [13]. These platforms bring together diverse user groups, forming multi-sided networks that enable data collection and use through various modes of production, consumption, collaboration, and sharing [13, 32].

Online digital platforms provide valuable opportunities for visualising distribution channels, including online shops and market places, as well as the exchange digital products and services [115]. These platforms are believed to have positive environmental and circularity impacts [116], by promoting the closing, slowing, and narrowing of material loops [117]. The environmental benefits and CE value arise from the information provided by these platforms regarding product availability and location. This information enhances users' access to shared use through sharing platforms and facilitates the exchange of goods via digital marketplaces. Furthermore, these digital platforms support increased data collection, promoting better end-of-life management, and enhancing residual value by enabling improved maintenance, repair, refurbishment, remanufacturing, and recycling [33, 115, 117, 118].

Online platforms provide a means to create new markets for secondary materials within the context of the CE, connecting supply and demand for various stakeholders, including individuals and companies [13, 33]. They can also play a crucial role in supporting innovative circular business models for product-service systems [117, 118] particularly in the construction industry, enhancing competitiveness and efficiency across the value chain [13, 119].

Depending on their operational context, digital platforms offer two primary types of exchanges: business-to-business (B2B) interactions, such as the Excess Material Exchange in the Netherlands [120], which promotes the elevated-value reuse of materials and waste across industries, and business-to-consumer (B2C) exchanges, like the Enviromate platform in the UK [121], which connects consumers with providers of leftover construction materials to encourage closed-loop resource utilisation.

The availability of these platforms and markets significantly influences social aspects [13], impacting user behaviours towards accepting CE products such as secondary construction materials and reclaimed goods, by creating favourable market conditions. These platforms also empower communities to co-create circular products and services [117] and support other social factors by serving as venues for job advertisements and demands for construction service providers within the construction industry.

The use of digital marketplaces and online platforms is widely supported by national and European legislation, exemplified by the EU's Digital Single Market strategy [119]. While many CE experts emphasise the value of establishing digital

platforms for circular material flows, the low number of users remains a significant challenge to the widespread adoption of these tools [118].

Despite the numerous advantages of digital platforms, only a few studies in the literature have addressed their potential, identifying two primary approaches. The first approach is known as tool-based platforms, which focus on the production processes of buildings, with BIM playing a key role. The second approach is collaboration platforms, which engage various stakeholders to improve the management aspects of building projects [117, 118].

17.2.14 Material Passports (MP)

Material Passports (MP), also known as digital passports or cradle-to-cradle passports, are comprehensive digital records that accompany physical products, serving as an auditable account of a product's entire lifecycle from design to EoL stages. These passports provide vital information about the product's composition, embedded material types, and grades [118]. They enumerate all the materials integrated into a product or construction project throughout its lifecycle. The primary objective of digital MPs is to facilitate circularity decisions in supply chain management by enabling the identification of opportunities for recovery, recycling, and re-use. The digitisation process plays a pivotal role in promoting circular buildings, with digital MPs serving as a crucial enabler in this transformative shift.

In the EU regulation, these passports are known as Digital Product Passports (DPPs) and are defined as "a structured collection of product-related data" encompassing "information related to sustainability, circularity, and value retention for reuse, remanufacturing, and recycling." As per the regulation, DPPs are required to furnish details regarding the origin and composition of materials, options for repair and disassembly, as well as avenues for recycling and disposal at the end of the product's life cycle [122]. However, for the effective implementation of DPPs in practical applications, there is a crucial need for a standardised format, structure, and terminology for these passports, which is currently lacking [123].

Digital MPs offer several advantages that contribute to improved sustainability, supply chain management, and compliance with regulations. Initially, they enhance data accessibility by providing comprehensive information about materials used in products or construction projects. This easily shareable data can be accessed by stakeholders throughout the supply chain, facilitating informed decision-making and promoting transparency. Digital MPs enable efficient material traceability, ensuring compliance with regulations and effective material management. By tracking materials throughout their lifecycle, these passports help ascertain their origins, a critical aspect in meeting regulatory requirements. This, in turn, promotes resource efficiency, reduces waste generation, and contributes to a more sustainable approach.

One of the significant advantages of digitalisation lies in its capacity to visualise the environmental impact along the entire value chain. Through the use of digital technologies such as BIM, stakeholders can make well-informed decisions regarding

intelligent design, production, and usage that enhance material and eco-efficiency. This visualisation aids in identifying opportunities to minimise waste and optimise resource utilisation, ultimately leading to more sustainable construction practices [124]. BIM has been widely investigated to develop digital MP that enhances design efficiency by minimising waste and environmental impacts. The key benefit of this automated approach lies in its ability to facilitate comparisons among various design variants. However, successful automation of MP generation necessitates accurate modelling in BIM, encompassing the appropriate use of BIM objects, geometry, materials, and other relevant components [125].

Costa and Hoolahan [126] provide guidance and a policy framework on implementing MPs to facilitate a CE in construction. Their recommendations include conducting pre-redevelopment audits, leading to pre-demolition/refurbishment audits, followed by the gathering of metric data, the implementation of an MP strategy, and incorporation of reused materials before construction commences. A deconstruction plan is then drafted before the building is handed over for use. The proposed MP strategy can be used to constitute Product Passports, which can subsequently be combined to produce System Passports. The MPs are based upon 'types', similar to 'levels' terminology used in other frameworks. These types were aligned with the Uniclass classification system and can then be combined into Element Passports and/or Building Passports.

17.3 The Role and Benefits of Digitalisation in Promoting More Circular Buildings

17.3.1 Managerial Value

Information Transfer for Improved Value Chain Management. Industry 4.0 has brought forth multiple technologies to aid sustainable and circular supply chain management by providing tools to support decision-making for the realisation of circular development in the construction industry [127]. The role of digitalisation in enabling efficient and cost-effective information transfer to support proper management is essential for fostering the CE and maximising its potential [128]. Information transfer among stakeholders across value chains remains a major challenge in implementing CE practices [129]. Fortunately, digital tools, platforms, databases, and other technological solutions can address this challenge by facilitating interactions between products, processes, and stakeholders throughout a project's lifecycle [130], thereby promoting closed material loops. These tools and solutions have the added advantage of collecting vast amounts of data, which is vital for implementing CE strategies such as maintenance, repair, lifecycle extension, and adaptive reuse of buildings.

Efficient information flow regarding sourcing, usage, durability, disposal, and recycling potential is crucial for optimising circular usage of products and materials

throughout their lifecycles. Seamless data transfer and sharing empower various stakeholders in the value chain, including suppliers, service providers, contractors, engineers, users, and waste operators, to adopt circular practices such as repair, maintenance, reuse, recycling, and proper disposal [129]. Digitalisation can offer opportunities for collaboration and integration among stakeholders in the construction industry, leading to business opportunities [129]. Information sharing platforms and BIM systems enable project teams to collaborate effectively and embed circularity objectives throughout the entire project lifecycle. By facilitating communication and knowledge exchange, digital technologies create an environment conducive to sustainable and circular transformation in the construction sector through circular feedback systems.

The synergies between CE and centralised management models in a digitalised environment, such as in BIM models, are highly appreciated for efficient information management and informed decision-making at various stages of a construction project's lifecycle, including planning, design, supply chain integration among other. The use of digital tools empowers stakeholders to make well-informed choices that align with circularity principles and promote sustainability at any stage of a project's lifecycle. While CE initiatives alone may not adequately address the complexity of systems and strategies to provide smart solutions for (EoL) and waste management, the integration of CE strategies within digitalised systems can enhance their effectiveness and efficiency [131].

Data Management. In today's resource-efficient CE, digitalisation and data availability are paramount for achieving optimal results. By harnessing digital tools, processes, and logistics in CE practices, they can be optimised, leading to increased efficiency and sustainability [132]. Online platforms, digital data, and product passports, among others, are revolutionising the way information is documented and shared, filling the gap of poor documentation and information loss that used to occur throughout the lifecycle of a building and its components due to changes that take place during different stages. These platforms and tools also serve certification purposes and are highly valued by academics and industry professionals as vital assets for maximising circularity potential in buildings and the built environment.

A fundamental aspect of data management in the CE is the creation of digital representations of buildings and their components, along with associated information. This approach offers several advantages for stakeholders involved in circular planning, design, and EoL solutions. Centralised digital models, such as BIM, have emerged as valuable tools for integrating diverse information related to buildings, elements, and geometry [133]. Stakeholders can access and leverage the information stored in these models to make informed decisions throughout the lifecycle of a building.

The development of digital technologies to monitor material flows and track data has been significantly amplified by BCTs. BCT plays a pivotal role in enabling efficient and effective reuse and recycling processes by securely storing, recording, and sharing important information about various materials and elements [133]. Through

BCs, the transparency and traceability of materials are enhanced, fostering trust among stakeholders and facilitating the implementation of circular practices.

Optimising individual processing steps and material flows along the value chain is critical for efficient resource management [132]. Digital data analytics plays a vital role in this regard by providing insights to predict materials requirements and enabling efficient supply–demand processes, resulting in significant time and cost savings. However, the extent of digitalisation determines the full potential of existing data. The higher the level of digitalisation, the more data can be processed and integrated for meaningful analysis. Increased data integration through digitalisation also facilitates the establishment of a historical path, offering valuable insights for future decision-making. Building such a data and digital wisdom requires a systematic data strategy that integrates multiple types of tools throughout the entire process, enabling robust and timely reactions to upcoming requirements.

17.3.2 Environmental Value

Circularity Implementation and Assessment Throughout the Building Lifecycle. The pivotal role of digitalisation in fostering the transition to a CE cannot be overstated. It harnesses the potential of digital technologies and interconnected objects, promising substantial reductions in resource consumption and the realisation of circular feedback systems [134].

Given the intricacy of buildings and the enormous resources they encapsulate, addressing the challenges of the building lifecycle necessitates a comprehensive, four-phase approach encompassing production, construction, operation, and EoL stages [26]. Although the operational phase of buildings is the longest and often the most environmentally impactful, it is crucial to recognise that the decisions made during the pre-use and design phases are pivotal. They significantly influence the operational performance of buildings, leading to substantial resource savings and reduced carbon emissions [26].

At the product level, digitalisation's role is particularly pronounced, offering easy access to product information critical for reducing resource consumption and optimising the product lifecycle. This accessibility empowers circularity options [135].

During the design phase, digital technologies play a critical role in implementing circularity strategies, expanding their impact on operational efficiency. Notably, digital parametric design tools are essential instruments for crafting regenerative building designs, while AI technologies, when integrated, enable extensive data interpretation and its application to design practices [26]. Moreover, digital tools support stakeholders to harness the value of circularity in buildings where circularity assessment necessities the handling of a large amount of information and data. Digital tools are perceived as great enablers for this process given their ability to address collection and management of data in a timely manner for efficient and effective assessments [136]. BIM provides a potential tool due to its potential to incorporate

complex data and automatise the assessment [137]. Recently, BIM-based circularity indicators have been introduced [138], e.g., Zhai [136] proposed a BIM framework to automate the circularity assessment of buildings from the early design stage. In the use phase, digital technologies play a vital role in extending a building's lifetime, thereby slowing the loop. They support repair and maintenance activities, offering scheduled maintenance and planned replacements. Moreover, they provide insights on how to safely replace and recover broken or EoL elements.

The EoL phase is a critical juncture for reintroducing building materials and resources into further cycles, in alignment with the waste hierarchy principles of reduce, reuse, and recycle, ultimately closing the loop. Multiple platforms and add-ins have been developed to facilitate and measure material recovery possibilities [26]. Integrating BIM into project processes opens new avenues for circularity, allowing the exploration and simulation of design and EoL options that enhance resource efficiency and minimise emissions. BIM acts as a decision-support tool by simulating and comparing multiple scenarios efficiently. It also automates various processes and calculations essential for making decisions at any stage of a building's lifecycle.

BIM's ability to centralise design and associated information empowers the examination of disassembly and deconstruction potential, paving the way for resource recovery at the end of a building's life [139]. For instance, the Disassembly and Deconstruction Analytics System (D-DAS) plug-in offers design engineers a powerful tool to assess EoL performance in the context of the CE [139]. The Design for Disassembly (DfD) functionality within this plug-in serves as a pivotal decision-support instrument, illustrating the impact of design and material choices on waste generation in the EoL phase.

Lifecycle Analysis (LCA) and Environmental Impacts. In the context of environmental sustainability, digitalisation plays a crucial role in decoupling economic activities from the depletion of natural resources and mitigating their environmental consequences. This objective aligns closely with the principles of a CE [13]. The fusion of circularity practices with digital technologies not only enhances environmental benefits but also provides a means to visualise the environmental impacts associated with different stages of the product life cycle along the value chain. This visualisation, in turn, facilitates environmentally-conscious design, production, and usage, ultimately increasing eco-efficiency [140].

Additive manufacturing tools like 3D printing help minimise the carbon footprint of some construction materials such as concrete. Comparing to conventional building techniques, 3D printing can significantly reduce emissions and energy consumption [140].

The integration of digital management models such as BIM and MPs with methods like Life Cycle Analysis (LCA) and Material Flow Analysis (MFA) holds the potential to significantly improve the efficiency of assessing a project's environmental performance [140]. By incorporating LCA methodologies into the design phase, these technologies enable the measurement and evaluation of resource consumption and environmental footprints right from the outset. Traditional manual LCA processes have been criticised for their time-consuming nature, but when integrated

into BIM, early assessment becomes possible, facilitating informed decision-making and highlighting opportunities for improvement. This, in turn, encourages the adoption of more sustainable practices. By continually tracking and monitoring resource usage throughout the construction process, digital technologies play a vital role in promoting circularity and minimising environmental impacts.

Numerous studies have explored the application of BIM-based LCA for evaluating and appraising design alternatives, starting from the early stages of a project's lifecycle, as exemplified by [141]. This approach extends the traditional use of LCA, which typically reported environmental impact and energy use at a specific point in a building's lifecycle for sustainability assessment and certification purposes. By incorporating LCA into the decision-making process, stakeholders can optimise material choices and design alternatives in line with circular construction principles. This approach addresses the previous constraint of time-consuming traditional LCA processes.

While many studies have focused on using BIM-supported LCA techniques for sustainability studies, the integration's potential has primarily revolved around certification purposes [141]. However, only a few have extended this research direction to support the circular design process and promote the use of circular materials.

Another study has integrated the LCA in the BIM-based MP which enabled a comparison between the environmental impacts and the reusability potential of buildings. The combined approach allows for optimisations of the building design in earlier design stages without neglecting the LCA or circularity impacts [142].

Multiple tools and BIM software plug-ins have been developed to enable BIM-based LCA by linking material libraries from BIM software with an LCA database. This integration permits the assessment of environmental impacts at different stages of a building's lifecycle. Many studies recognise the potential for extending this use to promote the implementation of CE principles. Such integration would enable stakeholders to achieve their circularity objectives without compromising other critical emissions and environmental aspects or, at the very least, minimise the trade-offs between these essential concepts.

Efficient Resource and Construction and Demolition Waste (CDW) Management. Fostering effective CDW management requires the use of advanced technologies that facilitate the efficient tracking of building elements. This, in turn, enables more streamlined and effective waste collection, separation, and redirection into circularity paths, including reuse, remanufacturing, repurposing, and recycling.

Sensor technologies, when combined with digital tools, offer the capability to plan waste routes and collections in real-time, based on demand [132]. An example of this combination is the Radio Frequency Identification (RFID) tags, which integrate sensors and identification technology through internet connectivity [13]. These RFID tags can be affixed to waste and recycling containers, facilitating the implementation of "Pay-as-you-throw" waste programmes in select cities, optimising municipal waste collection. These technologies provide real-time data storage, cloud processing, and seamless exchange of information between the cloud, waste collection vehicles, containers, recycling facilities, and secondary material retailers. This

comprehensive tracking system monitors container content characteristics and conditions, managing routes and productivity to ensure safe and cost-efficient sorting, reuse, and recycling [13].

In the pursuit of efficient CDW management, the role of IoT and BCT cannot be understated, as they play a pivotal role in storing, recording, and sharing critical information about various materials and elements [133].

Moreover, digital marking of materials, combined with AI, enhances the effectiveness of recycling processes, while digital marketplaces and platforms create channels and market conditions that promote the use of reclaimed materials [132].

BIM also plays a crucial role in establishing circular waste management channels. This tool, through a central information approach, aggregates data from diverse sources, including documents, on-site investigations, and the potential for reusing various building elements. This, in turn, aids in the accurate identification of components with circular value for recovery and urban mining [143]. By streamlining processes and promoting CE practices, BIM simplifies interconnected issues in the waste management landscape.

In the face of the challenges that stakeholders encounter when striving for high-quality work, maintaining efficiency, and addressing crucial aspects such as certification and waste management promotion, digital technologies continue to evolve, persistently offering solutions to tackle these concerns.

17.3.3 Economic Value

Cost Analysis and Life Cycle Costing (LCC). Life Cycle Costing (LCC) is a methodology employed to calculate the comprehensive expenses incurred throughout a product or system's entire life cycle. This aids in informed decision-making during the product development process [144, 145, 146]. LCC analysis allows for the comparison of products or systems in terms of the estimated costs involved over the project's entire life cycle. It therefore helps promote the most cost-effective design and process alternatives to achieve closed loop building life cycles. LCC contributes to managing circular businesses, cost reduction, and the mitigation of environmental impacts [144].

Applying LCC within a CE framework involves regarding products as composite entities comprising components and parts with distinct and multiple use cycles. In this context, evaluating products within a CE perspective necessitates extending their lifespan, with a focus on design elements such as repair, reuse, upgradability, disassembly, and recycling. Consequently, value retention processes (VRPs) become central in extending product lifespans and should be integrated into the evaluation. This approach encompasses post-use processes, providing practical and actionable insights to all stakeholders involved and enabling alignment with LCA methodologies [145].

A review of the literature highlights the possibilities, advantages, and challenges of integrating BIM and LCC [144, 147, 148]. While tools for integrating LCC and

LCA within BIM are available, it is important to note that these tools predominantly focus on new construction projects and lack examples demonstrating the assessment of circularity strategies' implications in existing assets, such as material salvaging and recycling [144]. Still, BIM can serve as a valuable tool for assessing LCC within a CE model in new and existing construction.

BIM streamlines the integration and visualisation of project data, enhancing the precision of LCC assessments. By connecting cost data to specific building elements and components, it enables precise calculations throughout the life cycle. Furthermore, BIM's parametric modelling capabilities support iterative design processes, optimising both performance and cost aspects [148, 149]. It offers early-stage decision support by evaluating the life cycle costs of design options and material choices, thereby facilitating the adoption of CE strategies for optimised resource utilisation and waste reduction [144]. BIM, in this way, fosters collaboration among stakeholders, promoting knowledge sharing and effective communication. This collaborative environment ensures that LCC considerations are integrated throughout the project life cycle, thereby enhancing transparency and informed decision-making [147]. During the operational phase, BIM's integration with facility management systems facilitates ongoing LCC evaluation. By monitoring energy consumption, maintenance costs, and performance data, BIM supports well-informed decisions regarding retrofits and renovations costs implications, thereby enhancing a building's CE performance [144].

Several challenges arise when implementing LCC and BIM integration, including the absence of standardised LCC cost estimation methods, unstructured and non-standardised data formats, interoperability issues, consistent and interpretable data sets, limitations on stakeholders directly involved in the model, and the need to clearly define system boundaries [145, 147].

New Business Models. Circular business models (CBMs) represent an innovative approach to harnessing the latent economic value present in products by extending their utility through closed material loops within an economic system [116]. These models outline how organisations create, deliver, and capture value within these closed loops, which consist of both forward and reverse supply chains that reintegrate reclaimed products [135]. CBMs promote product longevity, product reuse, residual value extraction from by-products, and enhancing product design and manufacturing efficiency [150]. They pivot around core elements of value proposition, delivery, creation, and capture, with an ever-growing emphasis on sustainability and circularity [151].

CBMs extend beyond environmental concerns, focusing on maximising product lifecycles across the entire supply chain. They aim to transform unusable products into new sources of value within the same or other supply chains. Effective collaboration between policymakers and companies is pivotal in either facilitating or hindering the development of CBMs through regulatory norms [152]. Hence, collaboration with a network of stakeholders, including suppliers, is vital for the development of circular solutions. CBM innovation is a system-wide phenomenon that demands interaction

among all stakeholders, encompassing both the core business network and external participants [153].

Nevertheless, businesses are often restrained by cost-centric models and existing partnerships that impede their engagement with circularity. A shift towards long-term value creation and consideration of non-economic benefits is imperative [151]. Current business modelling tools and methodologies often lack the requisite components for innovating CBMs comprehensively and disruptively. Embracing circularity requires maximising the value of products and materials, thereby reducing resource consumption and fostering positive societal and environmental outcomes. Incremental changes alone are inadequate; radical and transformative business models are indispensable to tackle prevailing challenges and usher in a CE.

A pivotal step is for companies to perceive their customers not as mere buyers but as users, thereby emphasising a shift from a product-centric approach to that of service provision. This transformation necessitates a redesign of value networks and associated business models to accommodate new players and evolving roles [153].

The core principles and components of CBMs can be drawn from the foundational principles of the CE. Numerous frameworks and definitions elucidate and characterise these components, including the ReSOLVE framework, circular value creation, normative prerequisites, and areas for integration [116]. Consequently, fundamental facets of CBMs encompass durability, renewability, reusability, repairability, upgradability, refurbishment, servitisation (e.g., product as a service like air conditioning), capacity sharing, and dematerialisation [152].

Digitalisation, driven by AI, IoT, big data, and online platforms, is revolutionising value chains across industries. These technologies can monitor and manage physical objects, generating extensive data on materials, products, and processes. By enabling optimised production systems and smarter products and services and creating a continuous information flow that mitigates market inefficiencies, digital tools can lead to reduced waste, longer product lifespans, and circular design. Thus, digitalisation fosters value creation and a more sustainable economy [154].

The commitment of managerial leadership is pivotal to the successful co-creation and co-capture of value [152]. CBMs thrive on a foundation of data and knowledge management. Different models require specific information at various stages of the value chain. In this regard, the use of digital tools can facilitate the adoption of CBM by:

- Sharing models (e.g., logistics, retail) rely on data like asset location and condition to connect users with what they need. Understanding user behaviour fuels personalised experiences.
- Product life extension models leverage data on product health and materials to optimise repair and reuse, keeping resources in circulation longer.
- Circular supply models depend on material composition and origin data to ensure transparency and efficient closed-loop systems. BCT plays a key role here.
- Resource recovery models (recycling, industrial symbiosis) require data on waste composition and reusability, along with knowledge about material life cycles, to transform waste into valuable secondary materials.

- Product service systems focus on providing access to services, not ownership. Data on product availability and condition, coupled with knowledge of user preferences, is crucial for smooth operation [154].

Effectively managing data and knowledge is essential for the success of diverse CBMs. It empowers them to operate efficiently and contribute to a more sustainable future. Each digital technology, through its combinatorial power and data processing capabilities, can address specific market failures that impede the scalability of circular activities. For example, combining online platforms, BCT, and AI can enable the creation of digital sourcing platforms that facilitate the exchange of products and materials at their optimal reuse potential [154].

Consequently, the implementation of CBMs necessitates a holistic perspective that spans all dimensions of value and encompasses numerous relationships along the value chain. Active engagement of stakeholders is imperative for value creation. Nonetheless, empirical evidence regarding the application of digital technologies for achieving CE goals remains limited. The transition to CBMs calls for ongoing monitoring, verification of achieved objectives, and prompt corrective measures. In this context, policymakers play a crucial role in steering the shift from a linear to a circular production model [152].

17.3.4 Social Value

Digital transformation stands as a widely recognised catalyst for economic and social progress. It serves as a potent instrument for unlocking the advantages of inclusive and sustainable growth, ultimately leading to enhanced societal well-being [13]. The advocacy for a digital CE in the construction and building industry brings forth numerous social advantages for both labourers and residents, contributing to the development of more inclusive and liveable communities. Digitalisation not only empowers consumers by involving them in product and service innovation but also enables companies to engage with their customers more effectively than ever before [153]. The integration of digital intelligence provides opportunities to disseminate knowledge, structure, ownership, and varying degrees of customisation, leading to more connected and enduring relationships with customers and end users [134].

Furthermore, by enabling digitalised planning, visualisation, and simulation of building and construction projects, professionals can enhance safety and comfort measures. Certain digital tools can also function as monitoring systems to ensure process quality and compliance with standards. The adoption of digital tools for circular construction necessitates a diverse range of skill sets, thereby creating new employment opportunities in the sector. However, this transformation calls for investment in training programmes to cultivate a skilled workforce capable of driving the transition towards a circular, sustainable built environment fortified with technological resilience.

Another critical dimension addressed by these tools is the challenge of access to affordable housing. By embracing circular design strategies that enable incremental construction, potential cost reductions can be realised. Additionally, the promotion of material health and the integration of principles to enhance air quality, passive techniques for thermal comfort, and energy efficiency needs can result in circular buildings that offer healthier living environments and comfortable spaces, positively impacting user well-being and overall quality of life.

17.4 Barriers and Critical Success Factors (CSF) for Digitalisation

17.4.1 Technical and Technological Challenges

Complexity of Buildings. The construction of buildings is an intricate and multifaceted process that involves the collaboration of various stakeholders throughout its different phases. Consequently, the complexity and fragmentation of the construction industry present a significant challenge for the successful integration of digital technologies [118]. To enhance the efficiency and effectiveness of construction projects through digitalisation, it is imperative that all stakeholders embrace digital transformation strategies for their internal and collaborative processes.

A critical issue highlighted by Berlak et al. [155] is the prevalence of imbalances within the industry. This imbalance arises when one company invests in digital technologies, while another remains resistant to such investments. The resistance of the latter inhibits the overall progress of digitalisation within the construction sector, irrespective of the efforts made by individual companies. This dynamic sheds light on why the level of digital adoption remains relatively low within the construction industry [155].

Lack of Integration and Interoperability Among Digital Tools. Numerous digital tools play a pivotal role in streamlining the construction process. However, a significant challenge arises from the lack of compatibility between these tools and the inadequate integration of hardware, software, and data channels. This integration shortfall hampers the full utilisation of digitalisation for specific construction purposes and inhibits its seamless application throughout the entire construction life cycle. Consequently, these tools often function independently, diminishing the overall effectiveness of digitisation [156]. This challenge of integration is further underscored by the findings of Yu et al. [101] and Zhang et al. [157], who highlighted the pressing need for seamless interoperability between digital tools to ensure uninterrupted operations. According to Yu et al. [101], the current level of technological integration falls short of facilitating the effective integration of a CE within the construction industry.

Lack of Standardisation. The digitalisation of the construction industry presents a significant challenge in the realm of standardisation for digital tools and devices.

This challenge stems from the fact that various digital transformation devices possess diverse requirements and constraints relating to energy consumption, data processing, security, and computational capabilities. Standardisation plays a pivotal role in harmonising these discrepancies in requirements and, in turn, streamlining the digitalisation process. However, the rapid pace of digital transformation often hinders the development of these much-needed standards [158].

As indicated by Olanipekun and Sutrisna [156], the absence of standardised practices restricts the effective implementation of digital tools within the construction sector. Without universally accepted guidelines for technology integration, companies face a reduced array of options when selecting digital tools for their ecosystem. This dearth of standardisation also poses a challenge when it comes to assessing the overall effectiveness of digitalisation efforts.

Zhang et al. [157] highlighted China's noteworthy contributions to the development of ISO standards for BIM. However, Olanipekun and Sutrisna [156] argued that the ISO guidelines for construction digital tools tend to overemphasise standardisation, neglecting the need for specific standards tailored to technologies widely employed across multiple industries. A prime example is 3D printing, which finds applications not only in construction but also in the manufacturing sector. Consequently, there is a need for a more nuanced approach to standardisation that accommodates the diverse needs of these multifaceted technologies.

Data Fragmentation and Insecurity. A large number of stakeholders throughout the construction value chain also creates the challenge of data fragmentation and its management. In a study of Bon-Gang et al. [159], the experts from Singapore construction companies identified data and information sharing as a critical challenge for effective smart technologies integration. They stated that this issue has a direct effect on the misuse and loss of data, misunderstanding within the team and inefficiencies within the project. Another study of Zhang et al. [157] revealed that data fragmentation is the most crucial challenge among technological barriers. The data fragmentation results in limitations in data sharing and negatively affect the digitisation of construction. This in turn leads to inefficient data sharing and data gap, miscommunication and conflicts, problematic information exchange between different stages, and data security.

With construction and built environment digitalisation processes, another crucial aspect that must be addressed is cyber-security. This broad and pressing topic presents several critical challenges. The challenge of data security is discussed in a study of Jemal et al. [130]. With the digitalisation of construction industry, a complex cyber network is created, that is prone to cyber-attacks. Nevertheless, the importance of data security has been neglected and led to significant threats of cyberattack. Therefore, the digitisation requires a proper cyber security infrastructure for construction companies. To mitigate these risks, various technologies can be leveraged. Encryption protocols, distributed database technology, cloud security, and BCT are instrumental in safeguarding key BIM components such as data ownership, data sharing, model federation, information workflows, data security, network security, and system security [160].

17.4.2 Resource Challenges

High Implementation Cost. Cost and investment capabilities are pivotal considerations for leaders in the construction industry when contemplating digital transformation [161]. Research underscores that the digitalisation of the construction sector incurs a substantial implementation cost, which is recognised as the most significant economic challenge faced by companies [157]. This high implementation cost is primarily attributed to the expensive equipment and extensive data storage requirements [158].

Lack of Expertise. The process of digitising the construction industry demands a proficient workforce equipped with cutting-edge digital skills. Unfortunately, a notable shortfall of digital technology experts in the construction sector has been documented in recent studies [162, 163]. The successful digital transformation of the construction field necessitates professionals specialising in machine learning, AI, data analytics, as well as hardware and software engineering [157]. This scarcity of skilled expertise has adverse repercussions on data processing and hinders the overall progress of digitalisation within the construction industry.

17.4.3 Cultural Challenges

It is essential to acknowledge that realising the full potential of digitalisation in promoting circular buildings necessitates more than just technological advancements. Institutional, behavioural, and socio-economic system changes are imperative to affect a transition towards a circular and digital economy. Collaborative efforts among various stakeholders, including policymakers, industry professionals, and consumers, are indispensable in creating a supportive environment that encourages circular building practices and maximises the benefits of digitalisation. In the construction industry, stakeholders often exhibit resistance to embracing technological advancements and tend to rely on existing tools and conventional practices. This resistance has a detrimental impact on the digitisation of the construction sector [101]. Bon-Gang et al. [159] identified the reluctance to adopt new technologies as a primary organisational challenge faced by construction companies. The resistance among stakeholders can be attributed to several factors, including a lack of expertise in modern digital technologies and their potential benefits, the presence of high risks and penalties associated with unsuccessful project completion, as well as deeply entrenched organisational cultures [101, 163]. Furthermore, this hesitation to adopt digital solutions is not confined to a specific level of the organisation. This reluctance has been also observed among both employees and top management [161]. Adding to the complexity of this issue, it has been also found that there is often insufficient support from company leadership, exacerbating employees' resistance to the adoption of digital technologies [162].

17.4.4 Critical Success Factors (CSF)

Given the barriers and challenges associated with the extensive integration of digitalisation within the construction and building sector, several critical success factors have emerged as pivotal in overcoming these hurdles, as follows:

Collaboration and Communication. Effective collaboration is a crucial element for successfully addressing the inherent complexities of the construction industry. Collaboration and communication are essential for fostering a shared vision and common interests among stakeholders and encouraging the collaborative implementation of digital technologies. This cooperative effort also serves to mitigate the challenges associated with data sharing, system integration, and standardisation [156, 159].

Professional Trainings. In today's rapidly evolving landscape, professional training in digital technologies is of paramount importance for the construction industry. This training not only equips the workforce with essential skills but also significantly amplifies the effectiveness of digitisation efforts within the sector. By elevating the understanding of digital transformation and its associated advantages, we empower individuals to become proficient experts and simultaneously diminish the barriers to embracing technological change. This transformative approach is pivotal in driving progress within the construction industry [159].

Government Incentives. In addition to organisations, it is imperative for governments to play an active role in promoting shared values and fostering digital literacy across the entire value chain. Furthermore, government incentives are pivotal in aiding companies to surmount the elevated integration costs associated with digitisation. With government support, businesses can harness their investment capabilities for professional training and preliminary testing. A noteworthy example of the effectiveness of government incentives can be found in Singapore's construction industry, which boasts a sophisticated BIM integration compared to many other countries [159].

17.5 Discussion and Conclusions

The technologies advanced by Industry 4.0 hold immense potential for bolstering CE models within the built environment. This study sheds light on the pivotal roles played by 14 digital technologies in supporting the dual transition towards sustainability and digitalisation. The analysis shows the numerous benefits of implementing these technologies to support an efficient and effective application of multiple circularity strategies by enabling real-time monitoring and control of production processes, enhance supply chain management, facilitate material reuse and recycling, and extend the lifespan of products [29]. Ultimately, these measures reduce the environmental

impact of economic activities, among other environmental, economic, and social benefits.

It is worth noting that the digital toolbox extends beyond the technologies discussed in this study. Among the additional digital tools and technologies with potential applications in the construction and building sector are:

- Robotics and Automation: These technologies enhance the efficiency, precision, and productivity of manufacturing processes. They also enable the implementation of flexible and agile manufacturing systems, allowing for product customisation and adaptation, thus reducing the need for new production [29]. Additionally, automated processes reduce errors and minimise waste generation.
- Cybersecurity: Cybersecurity measures are vital for protecting systems against unauthorised access and cyber threats. This is achieved through encryption, authentication protocols, regular system updates, and employee training in cybersecurity best practices.

Among the various technologies explored in this study, BIM stands out as the most prevalent technology in the construction sector. Nevertheless, BIM exhibits significant interactions with most of the other technologies, resulting in increased efficiency, effectiveness, and objectivity.

The analysis of diverse digital tools and technologies applicable to the construction sector reveals that their successful implementation necessitates collaboration among different stakeholders, including manufacturers, suppliers, and consumers [164]. It also demands a holistic approach that takes into account the entire life cycle of projects and associated products. This is because these digital technologies exhibit varying levels of interdependence throughout the life cycle of buildings, interacting with or depending on each other during the execution of specific tasks [118] which restricts their standalone use.

It is vital to acknowledge that, despite the numerous advantages and benefits these technologies offer to the environment, economy, and society, their improper application and mismanagement can introduce several threats at multiple levels. For instance, the increased connectivity of Industry 4.0 technologies may give rise to potential environmental risks that must be addressed to ensure sustainable CE practices. Some of these risks encompass increased energy consumption if the use of connected devices is not adequately managed, potentially leading to elevated greenhouse gas emissions and contributing to climate change [29]. Another risk involves the generation of electronic waste (e-waste), posing environmental hazards due to the presence of hazardous materials [29]. Furthermore, the heightened connectivity and data sharing in Industry 4.0 systems make them vulnerable to cybersecurity threats, which, if breached, can have environmental consequences, such as unauthorised access to control systems resulting in accidents or disruptions [29].

To mitigate these environmental risks and foster sustainable CE practices, several measures can be implemented as outlined by Laskurain-Iturbe et al. [29]:

- Enhancing energy efficiency practices and technologies to minimise the energy consumption of Industry 4.0 systems. This may involve optimising algorithms, utilising energy-efficient hardware, and adopting renewable energy sources.
- Establishing effective e-waste management systems that promote recycling, refurbishment, and responsible disposal of electronic devices. This may include implementing collection programmes, designing products for easy disassembly and recycling, and promoting the use of recycled materials in manufacturing.
- Implementing robust cybersecurity measures to safeguard Industry 4.0 systems against unauthorised access and cyber threats. This can encompass encryption, authentication protocols, regular system updates, and employee training on cybersecurity best practices.
- Conducting life cycle assessments of Industry 4.0 technologies and systems to identify and mitigate potential environmental impacts. This can help optimise resource utilisation, reduce waste generation, and identify opportunities for improvement throughout the product life cycle.
- Developing and enforcing regulations and standards that promote sustainable practices in the adoption and implementation of Industry 4.0 technologies. These regulations may include requirements for energy efficiency, e-waste management, and cybersecurity measures.

By addressing these environmental risks and implementing these measures, the integration of Industry 4.0 technologies into CE practices can be achieved sustainably and with a responsible approach.

Another essential challenge hindering the successful implementation of digital technologies in CE models is the absence of a well-defined regulatory framework that both upholds CE principles and promotes sustainable practices of digital technologies and tools. This obstacle is exacerbated by the substantial requirement for investments in novel technologies and infrastructure. Additionally, fostering a significant shift in mindset and culture is imperative, a task that proves challenging without robust leadership and active stakeholder engagement [164].

Despite these challenges, the thoughtful combination of Industry 4.0 and the CE in construction offers several benefits, including:

- Improved Resource Efficiency: Enhancing resource efficiency [6, 29, 165].
- Enhanced Sustainable Business Performance: Reducing demand for natural resources and extending product life cycles [165].
- Positive Environmental Impact: Minimising waste generation and promoting reuse and recycling of materials, resulting in a reduced environmental footprint [165].
- Collaboration and Transparency: Encouraging increased collaboration and transparency [165].
- Competitive Advantage: Offering a distinctive competitive advantage for companies [165].
- Improved Operational Performance: Increasing efficiency, productivity, and quality in operations [165].

All of these factors contribute to improved economic performance for companies, driven by synergistic effects between the CE and digitalisation, leading to increased resource efficiency, cost savings, and enhanced competitiveness [165]. Moreover, this approach also has the potential to reduce the demand for natural resources, decrease environmental impact, create local employment opportunities, and contribute to economic development in the region [165].

Nonetheless, further research and effort are required to:

- Identify the primary drivers and obstacles in the adoption of digital tools and technologies for promoting circularity practices in the construction sector.
- Explore innovative business models that facilitate the transition to a digital circular economy.
- Investigate the role of digital technologies and platforms, not only those addressed in this study but also potential ones.
- Assess the environmental and economic impact of digitalisation on circularity practices to provide compelling evidence of their benefits and guide decision-making.
- Evaluate the effectiveness of existing policies and regulations in advancing the shift towards a digital CE and pinpoint areas requiring improvement.
- Develop strategies to encourage collaboration and engagement among diverse stakeholders, including businesses, governments, and consumers, to drive the adoption of digitalised circular practices [165].

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