State of the art Technologies that Facilitate Transition of Built Environment into Circular Economy

Aparna Harichandran[1], Søren Wandahl[1] and Lars Vabbersgaard Andersen[1]

[1]Department of Civil and Architectural Engineering, Aarhus University, Denmark

aparnaharichandran@cae.au.dk, swa@cae.au.dk, lva@cae.au.dk

Abstract –

The construction industry is highly energy intensive and causes significant environmental impacts and reduction in natural resources. A radical change in current practices is necessary for achieving a circular economy in the construction sector. Structural holes in the supply chain, coordination of diverse stakeholders, and resource management at the end of life of buildings are some of the key challenges for implementation. Technologies that spearhead the industry transition and their contributions to realizing a circular built environment are reviewed in this study.

Keywords –

Circular Economy; Construction Industry; Digitalization; Sustainability.

1 Introduction

Conventional construction practices in the linear manner that follow "take, make, use, dispose" result in a considerably high consumption of natural resources and greenhouse gas (GHG) emissions [1]. With the built environment currently responsible for about 35% of the global energy consumption and 38% of carbon dioxide-equivalent (CO_2e) emissions [2], decarbonizing the sector is one of the most cost-effective ways to mitigate the worst effects of climate breakdown [3]. If global warming has to be contained to less than 1.5° C increase by the year 2050, the built environment needs to reduce the CO_2e emission by around 60 Gt [4]. In this context, there is a compelling need to adopt a regenerative and sustainable business model for the construction industry.

Circular Economy (CE) emerged as one of the holistic solutions for addressing resource requirements, climate challenges and developing a sustainable built environment. CE is rooted in several sustainability concepts such as industrial ecology, cradle-to-cradle (C2C), regenerative design and the blue economy system as illustrated in Figure 1 [5]. Numerous definitions of CE by researchers and industrial experts over the period often tend to create misunderstanding and lack of consensus. Therefore, Kirchherr et al. [6] analysed 114 definitions of CE for a comprehensive conceptualization. They have found that the definition by the Ellen MacArthur Foundation (EMF) is the most used among the 114 definitions. According to the EMF [7], CE is "an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." Introducing such a system in construction sector requires digitalization. This study presents the enabling technologies for CE in built environment. The role of each technology, their interdependencies and drawbacks are also evaluated.

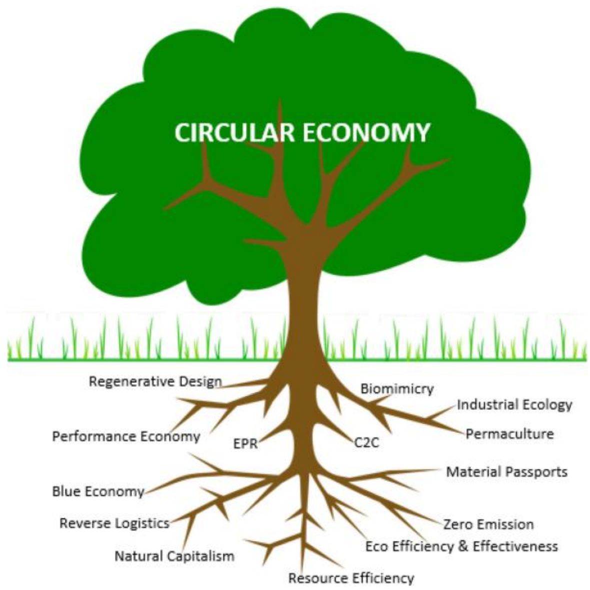

Figure 1 Sustainability concepts form the roots of circular economy [5]. (EPR: Extended Producer Responsibility, C2C: cradle-to-cradle)

The remaining parts of this paper are organised as follows. Section 2 describes a circular built environment framework. The methodology of this study is given in Section 3. The technologies that enable the transition of the built environment into a circular economy are provided in Section 4 and Section 5 concludes the paper.

2 A Circular Economy Framework for the Built Environment

Developing an integrated CE framework emphasising environmental sustainability is challenging due to the uniqueness of every construction project. A recent study proposed a comprehensive framework for implementing CE as illustrated in Figure 2 [8]. Building design aided by Building Information Modelling (BIM) enables accurate estimation of material quantities and the selection of sustainable alternatives of materials [9]. Sourcing materials from disassembled buildings and modularising and/or prefabricating new building components ensure material circularity [10]. Besides, the new design of building components should focus on deconstruction and disassembly at the end of life. The environmental impact caused by transporting raw building materials can be reduced by sustainable sourcing [11].

Firstly, material circularity can be incorporated during the service life of the building by using recycled materials from other cycles for refurbishing purposes [8]. Towards the end of the life of a building, the emphasis of CE shifts towards managing Construction and Demolition (C&D) waste. Developing an effective CE business model, controlling waste materials from the source, adopting strategic incentive plans and implementing technological innovations are some of the strategies for managing C&D waste [12]. Since the concepts of deconstruction are already incorporated during design, the building components can be retrieved at the end of life of the building. These components can be adequately repaired or retrofitted before supplying back to the materials selection stage for the next cycle. The C&D waste materials other than building components, such as recycled aggregates, scrap steel and wood, must be handled separately. These materials are subject to onsite sorting and screening before being recycled or reused for producing appropriate secondary materials. In the end, these sustainably sourced materials are either directly utilized for the next cycle of building construction or to produce prefabricated elements. Therefore, industrial ecology concepts have a direct influence on material circularity for the CE.

The development of a new CE business model for the built environment requires combined efforts from various stakeholders such as governments, researchers, designers, manufacturers, construction companies, recyclers, and suppliers. Each of these stakeholders contributes to diverse aspects from policy formulation, product design, and technology development to sustainable sourcing and construction practices.

3 Methodology

This study applied a systematic literature review to identify the key technologies that enable a circular built environment. The Scopus database is selected for searching the relevant literature. The scope of this study is limited to literature that explicitly mentions the term ‘circular economy’ along with the keywords for each technology. For example, “circular economy” AND (building OR construction) AND “blockchain”. After the initial search, the relevant articles were identified and analysed to assess the role of technologies in developing

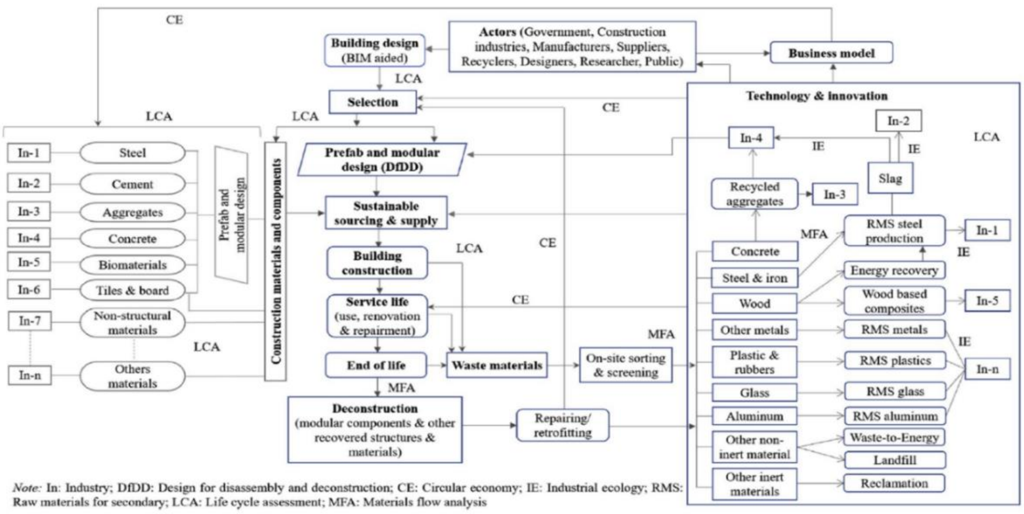

Figure 2 The framework for implementing CE in the built environment [8]

circular building strategies.

4 Enabling Technologies for Circular Economy in Built Environment

The conservative and fragmented nature of the construction industry is one of the significant barriers to CE. Several emerging technologies can accelerate the transformation of the industry [13]. Some of the most common and critical technologies identified from the literature are summarized in this section.

4.1 Artificial Intelligence

Due to the extensive applications in diverse fields of study, Artificial Intelligence (AI) has several definitions and understandings among scientific communities. In general, "AI leverages computers and machines to mimic the problem-solving and decision-making capabilities of the human mind" [14]. Several subdisciplines with diverse computing techniques constitute the continuously emerging discipline of AI. Machine Learning (ML) is a subfield of AI that trains algorithms to learn from data, while Deep Learning (DL) is a subfield of ML based on neural network algorithms [15]. Some of the existing and potential applications of AI in the construction industry include structural health monitoring, life cycle analysis, automated construction monitoring and material circularity [16], [17].

The EMF and Google identify that designing circular products, operating circular business models and optimizing infrastructure are the ways in which AI can assist in transforming to CE [18]. Çetin et al. [19] categorize the enabling functions of AI into three: 1) design optimization, 2) fault detection and requirement identification for buildings, and 3) applications to support end-of-life activities. Design optimization with ML can identify the best solution from numerous design alternatives based on desired performance criteria [20]. Besides, ML models can predict the carbon footprint of building designs at the early design stage [21]. Computer vision techniques are widely applied to identify faults in buildings through DL models [22]. Researchers have developed methods to identify the energy demands of buildings [23] and predict service life through ML models [24]. Categorizing demolition waste [25], estimating building component reusability [26], and detecting recycled aggregate composition [27] are some of the various ways AI supports end-of-life activities. The application of AI technologies for CE has several barriers such as the high cost of technology implementation, lack of technical expertise, need for large amounts of good quality data, and possibility of biases caused by training data.

4.2 Material Passports and Material Databanks

Comprehensive information on building resources at the end of life is unavailable. This lack of information is one of the greatest challenges for recycling and reusing construction materials [28]–[30]. According to some researchers, storing and maintaining the information of building components and materials in a digital environment from the early design stage to demolition is a solution [29], [31]. The concept of the Material Passport is formulated based on this idea. Material passports are digital datasets of objects that contain details such as properties, location, and ownership of the object. They are created and operated at various levels from city to building components in BIM or another digital platform. This concept is demonstrated by BAMB, an EU-funded project, by creating a platform with more than 300 material passports at three levels of detail [32]. Material passports were used to estimate environmental impacts of design alternatives [31], material quantities in a locality [33] or building circularity level [34]. Another concept introduced to address the lack of building resource information is material databank. The "material and component bank" proposed by Cai and Waldmann [30] is a BIM-based database run by an independent contractor. This database facilitates transferring demolition materials from one site to another for construction. Material passports and material databanks are new technology and have several challenges in adoption such as lack of standardisation, low adoption rate, need for data security and accurate information, and high implementation cost.

4.3 Building Information Modelling

BIM provides a comprehensive digital representation of products and processes related to built assets for facilitating interoperability during design, construction and management [35]. Engineers, architects, consultants, and other actors in the construction industry utilize BIM for numerous tasks such as quantity estimation, design alterations, planning and facility maintenance. Several contributions of BIM directly foster sustainable practices. One such example is enabling effective communication and information exchange between stakeholders to support alignment of project tasks and outcomes. Reducing the wastage of building resources through design optimization is another major contribution [36]. Sustainable design solutions can be generated with the help of existing commercial BIM software and their enhanced capabilities through plugins. Incorporation of Life Cycle Assessment (LCA) in the design phase [37] and performance optimization through analysis of the indoor environment are some of the significant contributions [38]. During the service life of a building, BIM can be used for performance monitoring [39], managing and tracing resources [40], and asset maintenance [41]. In addition to that BIM acts as the source of information that enables material passports and databanks [19]. Implementing BIM requires high cost, time, and resources. Besides, the outcome of BIM is affected by the quality of data input.

4.4 Digital Twins

Digital Twins (DT) are the digital version of physical assets that can provide decision support and control feedback for monitoring and maintaining physical assets. According to Arup [42], "A digital twin is the combination of a computational model and a real-world system, designed to monitor, control and optimise its functionality. Through data and feedback, both simulated and real, a digital twin can develop capacities for autonomy and to learn from and reason about its environment." This emerging technology has wide applications in various industries such as manufacturing, aerospace, consulting, and construction. However, the level of details, maturity and possible extent of control varies with the complexity of the physical systems. The DT can be developed for components, assets, processes, systems or networks of systems [42]. A construction process DT may differ from the DT for aircraft maintenance. The construction DT combines geometric information from BIM and data from sensor networks for data analysis and decision support with intelligent algorithms. The service life of buildings can be extended by predictive maintenance. Integrating material passports with DT enables predictive maintenance [43]. Besides, combining these technologies also helps in reusing material during deconstruction [19]. The DT also supports flexible space utilization in buildings. For example, the DT platform of the EDGE Olympic Office allows people to customize their working spaces [44]. Digital Twin technology is relatively new, and some drawbacks include the lack of standardisation, limited scalability in large projects, the complexity of DT models, and privacy concerns caused by cyber-attacks.

4.5 Big Data Analytics

Big Data Analytics (BDA) applies advanced analytic techniques on exceptionally large datasets that are diverse in composition, source, and structure to derive meaningful information for decision support. Big data refers to the datasets that cannot be processed or managed by conventional relational databases with low latency due to their size or type [45]. In addition to size, heterogeneity, authenticity, value, and speed of processing are some other distinguishing characteristics of big data [46]. Each stage of construction generates a large amount of data from various sources including BIM, monitoring devices and sensors. Combining other technologies such as BIM, AI and the Internet of Things (IoT), BDA can offer several solutions for material wastage, resource constraints and energy expenditure [47]. Machine Learning algorithms improve their performance while trained with good-quality big data. These algorithms can be applied for creating low-carbon building designs [48] and for assisting tools for generative designs [47]. Besides, ML algorithms fuelled by big data provide decision support during the design [49] and operational phases of a building [50]. The decisions during the design phase may include selecting the right parameters, while for the operation phase they may direct towards improving the energy performance or extending the service life by predictive maintenance. Time-intensive analysis, limited availability of data, high cost of implementation, and low quality of construction data are some of the challenges for employing BDA.

4.6 Blockchain

Blockchain technology offers secure electronic transactions of tangible and intangible assets without intermediaries. Distributed ledgers that allow access to all participants, immutable records that cannot be altered, and smart contracts with stipulated conditions which automate business logic are the key characteristics of blockchain [51]. Transparent and secure transactions with the consensus of all the stakeholders through blockchain enable good business collaborations. The potential of blockchain technology has been extensively focused on developing cryptocurrencies in the earlier days. This technology can be explored for various applications in the construction industry such as tracking the revisions of BIM models, managing material passports, keeping ownership records of assets and automating stakeholder transactions [52]. The fragmented supply chain of the construction industry can be improved by transparent value transactions and efficient information management through blockchain technology [53], [54]. Coupled with the IoT, blockchain can deliver intelligent product services for prefabricated construction [55]. The most significant impact of blockchain is enabling material passports by transparent information flow across supply chain networks at various stages of the building lifecycle [56]. Trustful and collaborative trading networks can be created through this technology by offering secure transactions. One such example is a user-friendly community-based energy trading platform called Pando [57]. The adoption of blockchain requires significant computing power and money. Additionally, it may raise regulatory challenges including cyber security and legal liability.

4.7 The Internet of Things

The IoT refers to the technology that enables equipment connected with sensors or identifiers to communicate with the user or with other equipment through interoperable networks [58]. These networks of connected devices are created through various techniques including cloud computing and wireless sensor networks. Home automation with smart devices and security systems is one of the ubiquitous applications of the IoT. Tracing the building components throughout the building lifecycle is one of the biggest challenges to be addressed for material circularity. Researchers have identified the potential of IoT technology combined with Radio Frequency Identification System (RFID) for tracing the building components physically and digitally [55], [59]. The connected devices in the IoT network produce numerous data that can be utilized to generate meaningful information through BDA. Optimizing the energy performance of a building through IoT enabled lighting system is an example [60]. Assessing the conditions of a building through an embedded sensor system and predicting the maintenance requirements can prolong the service life of buildings [61]. Flexible use of building spaces through monitoring occupancy [62] and improving thermal comfort through controlling HVAC (Heating, Ventilation, and Air Conditioning) systems are other applications of IoT technology [63]. In addition to the high implementation cost and maintenance cost, IoT poses challenges such as the management of large quantities of data, environmental impacts due to high power consumption and discarding of IoT devices, and reliability issues caused by malfunctioning devices.

4.8 Extended Reality

Immersive technologies have grown beyond the realm of entertainment and reached to complex and innovative applications in other industries. According to Unity [64], Extended Reality (XR) refers to “technology-mediated experiences that combine virtual and real-world environments and realities” and stands as a generic terminology for Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Digital contents are overlayed in the real world to create AR. The users fully immerse in digitally created visuals that replace the real world to experience VR. The MR technology blends the real world and digital content to allow seamless interactions between these entities. The construction industry is yet to exploit the immense potential of XR for creating various sustainability solutions that involve visualisation and interaction. The XR technology aids immersive visualisation of the design alternatives and building models generated through BIM. This improves communication and consensus among stakeholders and allows correction in the early stages of design and avoids reworks during construction [65]. The contractors, foremen, and workers can take scheduled virtual tours of the construction sites to reduce mistakes in the upcoming construction activities and associated wastages of materials. Construction safety training assisted by VR technology teaches the labours to navigate various construction accidents in a way that is not possible by conventional training methods [66], [67]. In addition to productivity improvement, loss of time and wastage due to construction accidents or injuries can be avoided by these advanced training techniques. The XR technology can also assist in various end-of-life activities such as planning deconstruction and material logistics between construction sites [68]. The demerits of XR technology include the need for specialised equipment and skillset, the high cost of implementation and maintenance, and sustainability concerns caused by the production and disposal of equipment.

5 Conclusions

Consumeristic and user-centric practices in the construction industry have resulted in significant environmental impacts and reduction in natural resources. A paradigm shift towards the circular economy is necessary for the built environment. Several studies propose theoretical frameworks for implementing circularity principles. Structural holes in the supply chain, coordination of diverse stakeholders, and management of resources at the end of life of buildings are some of the key challenges for implementation. Several independent studies were conducted to apply various technologies in the construction industry. However, only a few of the studies have focused on identifying the technologies and how they facilitate the transition of the built environment into a circular economy. Therefore, this study provides a review of the state of the art technologies and how they enable a circular built environment.

References

[1] G. L. F. Benachio, M. do C. D. Freitas, and S. F. Tavares, “Circular economy in the construction industry: A systematic literature review,” *J. Clean. Prod.*, vol. 260, 2020.

[2] United Nations Environment Programme, “2020 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector - Executive Summary,” 2020.

[3] S. Wandahl, C. T. Pérez, S. Salling, H. H. Neve, J. Lerche, and S. Petersen, “The impact of construction labour productivity on the

renovation wave," *Construction Economics and Building*, vol. 21, no. 3. Australian Institute of Quantity Surveyors, pp. 11–32, 2021.

[4] H. Wang, W. Chen, and J. Shi, "Low carbon transition of global building sector under 2- and 1.5-degree targets," *Appl. Energy*, vol. 222, pp. 148–157, 2018.

[5] O. E. Ogunmakinde, W. Sher, and T. Egbelakin, "Circular economy pillars: a semi-systematic review," *Clean Technol. Environ. Policy*, vol. 23, no. 3, pp. 899–914, 2021.

[6] J. Kirchherr, D. Reike, and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," *Resour. Conserv. Recycl.*, vol. 127, pp. 221–232, 2017.

[7] Ellen MacArthur Foundation (EMF), "Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition," 2012.

[8] M. U. Hossain, S. T. Ng, P. Antwi-Afari, and B. Amor, "Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction," *Renew. Sustain. Energy Rev.*, vol. 130, 2020.

[9] L. A. Akanbi *et al.*, "Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator," *Resour. Conserv. Recycl.*, vol. 129, pp. 175–186, 2018.

[10] H. Helander, A. Petit-Boix, S. Leipold, and S. Bringezu, "How to monitor environmental pressures of a circular economy: An assessment of indicators," *J. Ind. Ecol.*, vol. 23, no. 5, pp. 1278–1291, 2019.

[11] M. U. Hossain, A. Sohail, and S. T. Ng, "Developing a GHG-based methodological approach to support the sourcing of sustainable construction materials and products," *Resour. Conserv. Recycl.*, vol. 145, pp. 160–169, 2019.

[12] B. Huang, X. Wang, H. Kua, Y. Geng, R. Bleischwitz, and J. Ren, "Construction and demolition waste management in China through the 3R principle," *Resour. Conserv. Recycl.*, vol. 129, pp. 36–44, 2018.

[13] F. Elghaish, S. T. Matarneh, D. J. Edwards, F. Pour Rahimian, H. El-Gohary, and O. Ejohwomu, "Applications of Industry 4.0 digital technologies towards a construction circular economy: gap analysis and conceptual framework," *Constr. Innov.*, vol. 22, no. 3, pp. 647–670, 2022.

[14] IBM, "What is Artificial Intelligence (AI)?," *IBM Cloud Education*, 2020. https://www.ibm.com/cloud/learn/what-is-artificial-intelligence (accessed Aug. 02, 2022).

[15] IBM, "AI vs. Machine Learning vs. Deep Learning vs. Neural Networks: What's the Difference?," *IBM Cloud*, 2020. https://www.ibm.com/cloud/blog/ai-vs-machine-learning-vs-deep-learning-vs-neural-networks (accessed Aug. 04, 2022).

[16] S. K. Baduge *et al.*, "Artificial intelligence and smart vision for building and construction 4.0: Machine and deep learning methods and applications," *Autom. Constr.*, vol. 141, p. 104440, 2022.

[17] A. Harichandran, B. Raphael, and A. Mukherjee, "Equipment activity recognition and early fault detection in automated construction through a hybrid machine learning framework," *Comput. Civ. Infrastruct. Eng.*, vol. 38, no. 2, pp. 253–268, 2023.

[18] Ellen MacArthur Foundation (EMF) and Google, "Artificial intelligence and the circular economy - AI as a tool to accelerate the transition," 2019.

[19] S. Çetin, C. De Wolf, and N. Bocken, "Circular digital built environment: An emerging framework," *Sustain.*, vol. 13, no. 11, 2021.

[20] V. J. L. Gan, I. M. C. Lo, J. Ma, K. T. Tse, J. C. P. Cheng, and C. M. Chan, "Simulation optimisation towards energy efficient green buildings: Current status and future trends," *J. Clean. Prod.*, vol. 254, p. 120012, 2020.

[21] M. Płoszaj-Mazurek, E. Ryńska, and M. Grochulska-Salak, "Methods to Optimize Carbon Footprint of Buildings in Regenerative Architectural Design with the Use of Machine Learning, Convolutional Neural Network, and Parametric Design," *Energies 2020, Vol. 13, Page 5289*, vol. 13, no. 20, p. 5289, 2020.

[22] Arcadis, "Artificial Intelligence in the AEC Industry – a Code of Practice." https://www.arcadis.com/en/knowledge-hub/blog/global/susanne-knorr/2020/the-future-of-architecture,-engineering,-and-construction-is-digital-and-intelligent (accessed Aug. 29, 2022).

[23] M. U. Mehmood, D. Chun, Zeeshan, H. Han, G. Jeon, and K. Chen, "A review of the applications of artificial intelligence and big data to buildings

for energy-efficiency and a comfortable indoor living environment," *Energy Build.*, vol. 202, p. 109383, 2019.

[24] W. Z. Taffese and E. Sistonen, "Machine learning for durability and service-life assessment of reinforced concrete structures: Recent advances and future directions," *Autom. Constr.*, vol. 77, pp. 1–14, 2017.

[25] P. Davis, F. Aziz, M. T. Newaz, W. Sher, and L. Simon, "The classification of construction waste material using a deep convolutional neural network," *Autom. Constr.*, vol. 122, p. 103481, 2021.

[26] K. Rakhshan, J. C. Morel, and A. Daneshkhah, "A probabilistic predictive model for assessing the economic reusability of load-bearing building components: Developing a Circular Economy framework," *Sustain. Prod. Consum.*, vol. 27, pp. 630–642, 2021.

[27] J. D. Lau Hiu Hoong, J. Lux, P. Y. Mahieux, P. Turcry, and A. Aït-Mokhtar, "Determination of the composition of recycled aggregates using a deep learning-based image analysis," *Autom. Constr.*, vol. 116, p. 103204, 2020.

[28] M. Honic, I. Kovacic, G. Sibenik, and H. Rechberger, "Data- and stakeholder management framework for the implementation of BIM-based Material Passports," *J. Build. Eng.*, vol. 23, pp. 341–350, 2019.

[29] M. R. Munaro, A. C. Fischer, N. C. Azevedo, and S. F. Tavares, "Proposal of a building material passport and its application feasibility to the wood frame constructive system in Brazil," in *IOP Conference Series: Earth and Environmental Science*, 2019, vol. 225, no. 1, p. 012018.

[30] G. Cai and D. Waldmann, "A material and component bank to facilitate material recycling and component reuse for a sustainable construction: concept and preliminary study," *Clean Technol. Environ. Policy*, vol. 21, no. 10, pp. 2015–2032, 2019.

[31] M. Honic, I. Kovacic, and H. Rechberger, "Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study," *J. Clean. Prod.*, vol. 217, pp. 787–797, 2019.

[32] L. Luscuere, R. Zanatta, and D. Mulhall, "Deliverable 7- Operational Materials Passports," Brussels, Belgium, 2019.

[33] O. Oezdemir, K. Krause, and A. Hafner, "Creating a Resource Cadaster—A Case Study of a District in the Rhine-Ruhr Metropolitan Area," *Build. 2017, Vol. 7, Page 45*, vol. 7, no. 2, p. 45, 2017.

[34] Madaster, "Madaster - The Materials Cadastre." https://madaster.com/ (accessed Aug. 30, 2022).

[35] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Architects, Engineers, Contractors, and Fabricators*, 3rd ed. Hoboken, NJ, USA: John Wiley and Sons, 2018.

[36] K. din Wong and Q. Fan, "Building information modelling (BIM) for sustainable building design," *Facilities*, vol. 31, no. 3, pp. 138–157, 2013.

[37] K. Xue *et al.*, "Bim integrated lca for promoting circular economy towards sustainable construction: An analytical review," *Sustain.*, vol. 13, no. 3, pp. 1–21, 2021.

[38] S. Habibi, "The promise of BIM for improving building performance," *Energy Build.*, vol. 153, pp. 525–548, 2017.

[39] J. M. Davila Delgado and L. O. Oyedele, "BIM data model requirements for asset monitoring and the circular economy," *J. Eng. Des. Technol.*, vol. 18, no. 5, pp. 1269–1285, 2020.

[40] Y.-H. He *et al.*, "BIM and Circular Design," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 225, no. 1, p. 012068, 2019.

[41] X. Gao and P. Pishdad-Bozorgi, "BIM-enabled facilities operation and maintenance: A review," *Advanced Engineering Informatics*, vol. 39. pp. 227–247, 2019.

[42] Arup, "Digital Twin towards a meaningful framework." https://www.arup.com/perspectives/publications/research/section/digital-twin-towards-a-meaningful-framework (accessed Aug. 11, 2022).

[43] F. Kedir, D. F. Bucher, and D. M. Hall, "A Proposed Material Passport Ontology to Enable Circularity for Industrialized Construction," *Proc. 2021 Eur. Conf. Comput. Constr.*, vol. 2, pp. 91–98, 2021.

[44] EDGE, "EDGE Olympic Amsterdam." https://edge.tech/developments/edge-olympic-amsterdam (accessed Sep. 01, 2022).

[45] IBM, "Big Data Analytics." https://www.ibm.com/analytics/big-data-analytics (accessed Aug. 30, 2022).

[46] S. Yin and O. Kaynak, "Big Data for Modern Industry: Challenges and Trends," *Proc. IEEE*, vol. 103, no. 2, pp. 143–146, 2015.

[47] M. Bilal *et al.*, "Big Data in the construction industry : A review of present status , opportunities , and future trends," *Adv. Eng. Informatics*, vol. 30, no. 3, pp. 500–521, 2016.

[48] M. Płoszaj-Mazurek, E. Ryńska, and M. Grochulska-Salak, "Methods to Optimize Carbon Footprint of Buildings in Regenerative Architectural Design with the Use of Machine Learning, Convolutional Neural Network, and Parametric Design," *Energies 2020, Vol. 13, Page 5289*, vol. 13, no. 20, p. 5289, 2020.

[49] G. Bressanelli, F. Adrodegari, M. Perona, and N. Saccani, "Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies," *Sustain. 2018, Vol. 10, Page 639*, vol. 10, no. 3, p. 639, 2018.

[50] C. Fan and F. Xiao, "Mining big building operational data for improving building energy efficiency: A case study," *J. Build. Serv. Eng. Res. Technol.*, vol. 39, no. 1, pp. 117–128, 2017.

[51] IBM, "What is Blockchain Technology? - IBM Blockchain." https://www.ibm.com/topics/what-is-blockchain (accessed Aug. 30, 2022).

[52] J. J. Hunhevicz and D. M. Hall, "Do you need a blockchain in construction? Use case categories and decision framework for DLT design options," *Adv. Eng. Informatics*, vol. 45, p. 101094, 2020.

[53] A. Böckel, A. K. Nuzum, and I. Weissbrod, "Blockchain for the Circular Economy: Analysis of the Research-Practice Gap," *Sustain. Prod. Consum.*, vol. 25, pp. 525–539, 2021.

[54] A. Shojaei, "Exploring applications of blockchain technology in the construction industry," *ISEC 2019 - 10th Int. Struct. Eng. Constr. Conf.*, 2019.

[55] C. Z. Li *et al.*, "A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction," *J. Clean. Prod.*, vol. 286, p. 125391, 2021.

[56] Arup, "Blockchain and the built environment." https://www.arup.com/perspectives/publications/research/section/blockchain-and-the-built-environment (accessed Sep. 01, 2022).

[57] Pando, "LO3 Energy." https://lo3energy.com/ (accessed Sep. 01, 2022).

[58] A. B. Lopes de Sousa Jabbour, C. J. C. Jabbour, M. Godinho Filho, and D. Roubaud, "Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations," *Ann. Oper. Res.*, vol. 270, no. 1–2, pp. 273–286, 2018.

[59] I. Bertin, R. Mesnil, J. M. Jaeger, A. Feraille, and R. Le Roy, "A BIM-Based Framework and Databank for Reusing Load-Bearing Structural Elements," *Sustain. 2020, Vol. 12, Page 3147*, vol. 12, no. 8, p. 3147, 2020.

[60] Interact, "Interact IoT lighting." https://www.interact-lighting.com/global (accessed Sep. 02, 2022).

[61] A. Katona and P. Panfilov, "Building Predictive Maintenance Framework for Smart Environment Application Systems," pp. 460–0470.

[62] Deloitte, "MAPIQ." https://www.resources.mapiq.com/customer-story/deloitte (accessed Sep. 02, 2022).

[63] Deloitte, "GR15: The edge of tomorrow." https://www2.deloitte.com/sk/en/pages/about-deloitte/articles/gx-the-edge-of-tomorrow.html (accessed Sep. 02, 2022).

[64] Unity, "Glossary of Terms & Acronyms for Immersive Technology." https://unity.com/how-to/what-is-xr-glossary (accessed Aug. 29, 2022).

[65] E. Jamei, M. Mortimer, M. Seyedmahmoudian, B. Horan, and A. Stojcevski, "Investigating the Role of Virtual Reality in Planning for Sustainable Smart Cities," *Sustain. 2017, Vol. 9, Page 2006*, vol. 9, no. 11, p. 2006, 2017.

[66] A. Harichandran and J. Teizer, "A Critical Review on Methods for the Assessment of Trainees' Performance in Virtual Reality-based Construction Safety Training," in *29th EG-ICE International Workshop on Intelligent Computing in Engineering*, 2022, pp. 439–448.

[67] A. Harichandran and J. Teizer, "Automated Recognition of Hand Gestures for Crane Rigging using Data Gloves in Virtual Reality," in *39th International Symposium on Automation and Robotics in Construction (ISARC 2022)*, 2022, pp. 304–311.

[68] T. M. O'grady, N. Brajkovich, R. Minunno, H. Y. Chong, and G. M. Morrison, "Circular Economy and Virtual Reality in Advanced BIM-Based Prefabricated Construction," *Energies 2021, Vol. 14, Page 4065*, vol. 14, no. 13, p. 4065, 2021.