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APPLICATIONS OF INDUSTRY 4.0 DIGITAL TECHNOLOGIES TOWARDS A CONSTRUCTION CIRCULAR ECONOMY: THEMATIC, GAP ANALYSIS AND CONCEPTUAL FRAMEWORK

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The authors wish to extend thanks to the editor, and the reviewers for their constructive comments and suggestions. The paper reads much improved as a result of addressing this positive feedback. Each individual comment has either been addressed or defended as appropriate (refer below), and a final file resubmitted for your consideration.

Once again, thank you.

Reviewer 1

Item No.	Comments	How we addressed the comment
1	The paper needs to be proofread please pay attention to punctuation e.g. page 1 line 14, page 16 line 50 etc.	Thanks for your comments. The paper is professionally proofreading and all mentioned errors are corrected.
2	Figure 3 has upside-down text (horizontal text) that needs to be corrected	Thanks for your comment. The figure is flipped only to maintain the quality, however, in the proofing stage, the publisher will return it to the normal position.

Reviewer 2

Item No.	Comments	How we addressed the comment
1	Yes, it is an interesting and timely paper based on a review of literature. This work examines a theme of potential relevance to this Journal.	Many thanks for your positive comment on our work.
2	The introduction section is not well structured, I believe it is necessary to specify in a clearer way the theoretical background, research purpose and to introduce briefly the research gaps. The theoretical framework needs to be strengthened and integrated with significative studies that emphasize the	Noted and agreed. The introduction has been restructured per your recommendation. The theoretical solution as a conceptual framework only shows the integration of different technologies based on the analysed research contributions and limitations. As such, authors relied on the analysed research in previous sections to develop the conceptual framework.

	relevance of Industry 4.0 technologies and circular economy.	
3	Methodology is appropriate and robust. However it would be good to develop an inclusion and exclusion criteria of studies in a tabular form.	Many thanks for your comment. Authors have clarified the inclusion criteria that were used to manually select and refine papers in the revised version.
4	The importance of the paper should be clarified in introduction and conclusion sections. The theoretical and practical implications are missing. Limits must also be integrated as they are not clearly highlighted.	Thanks for bringing this to our attention. Authors added one new section to highlight the practical implications and limitation. Moreover, the introduction now highlights the importance and the motivation of conducting such research.
5	Yes, quality of communication is good. However, grammar, spelling and references should be checked throughout the paper.	Many thanks for your comment. The paper has been professionally proofreading.

APPLICATIONS OF INDUSTRY 4.0 DIGITAL TECHNOLOGIES TOWARDS A CONSTRUCTION CIRCULAR ECONOMY: THEMATIC, GAP ANALYSIS AND CONCEPTUAL FRAMEWORK

Abstract

Purpose: This paper explores the emerging relationship between Industry 4.0 (I4.0) digital technologies (e.g., blockchain, Internet of Things (IoT) and Artificial Intelligence (AI)) and the construction industry's gradual transition into a circular economy (CE) system to foster the adoption of circular economy in the construction industry.

Design/methodology/approach: A critical and thematic analysis conducted on 115 scientific papers reveals a noticeable growth in adopting digital technologies to leverage a CE system. Moreover, a conceptual framework is developed to show the interrelationship between different industry 4.0 technologies to foster the implantation of CE in the construction industry.

Findings: Most of the existing body of research provides conceptual solutions rather than developing workable applications and the future of smart cities. Moreover, the coalescence of different technologies is highly recommended to enable tracking of building assets' and components' (e.g., fixtures and fittings and structural components) performance, which enables users to optimize the salvage value of components reusing or recycling them just-in-time and extending assets' operating lifetime. Finally, circular supply chain management must be adopted for both new and existing buildings to realise the industry's CE ambitions. Hence, further applied research is required to foster CE adoption for existing cities and infrastructure that connects them.

Originality/value: This paper investigates the interrelationships between most emerging digital technologies and circular economy and concludes with the development of a conceptual framework to integrate IoT, blockchain and AI into the operation of assets to direct future practical research applications.

Keywords:

Construction Circular Economy; Emerging digital technologies; Industry 4.0; Blockchain; Internet of Things (IoT); Artificial Intelligence (AI).

1. Introduction

The construction sector is inextricably linked to economic development, and globally, it employs around 7% of the workforce and represents 13% of the Gross Domestic Product

(GDP) (Filipe Barbosa, 2017). Yet, the sector is also the most resource-intensive in industrialized countries, creating approximately a third of global waste and at least 40% of carbon dioxide (CO_2) emissions (Miller, 2021). Moreover, unprecedented population growth in the world's sprawling urbanized areas is exponentially increasing by 200,000 people per day, all of whom need affordable housing and infrastructure, thus, posing a significant environmental challenge to the sector worldwide (Solas, 2016). A linear economy model currently shapes the process, which starts with extracting, producing, using, and finally disposing of building materials but inadvertently exposes industry stakeholders (i.e., contractors, clients and members of the supply chain) to various risks, particularly higher resource prices and supply disruptions. Anthropogenic pollution, natural resource depletion and the compelling need to harmonise the built and natural environments in a sustainable balance provided the trigger to shift the paradigm to a circular economy (CE) model. CE is premised upon extending materials' (or composite materials contained in goods) lifespan, decreasing waste through efficient design and material use and eliminating pollution. The Ellen McArthur Foundation define CE as: *"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"* (EllenMacArthurFoundation, 2015).

CE adoption is an emergent global phenomenon that continues to gather momentum. For example, the Japanese Government took the early initiative in 2008 and introduced the: *"the Law for the Promotion of the Circular Economy"* to shift to the CE model (Su *et al.*, 2013). In congruence, the European Union developed the horizontal standardized methods in the "CEN/TC 350/SC 1 - Circular Economic in the Construction Sector", which sought to consider operational and embodied carbon emissions in new buildings design (Gervasio, 2018). Simultaneously, interest in the unabated digital transformation is increasing worldwide (particularly in Europe) (EuropeanCommission, 2021) to support the transformation to a circular economy model in business. Digital technologies (DTs) (Alizadehsalehi and Yitmen, 2021; Götz *et al.*, 2020; Kor *et al.*, 2022; Ogunseiju *et al.*, 2021) which fall under the umbrella concept of Industry 4.0 (I4.0) technologies (Newman *et al.*, 2021), are viewed as the main enabler to transform the sector to a CE approach (Bressanelli *et al.*, 2018).

Complementary to those DTs and their applications to support CE implementation, many scholars have explored the links between CE and other approaches such as I4.0 and reverse logistics. A combination of I4.0 and CE approaches has witnessed several new etymological hybrid transitions within the academic literature, such as Circular I4.0 and Digital CE (Gupta *et al.*, 2021; Hossain *et al.*, 2020a; Nascimento *et al.*, 2019; Rahimian *et al.*, 2021). Such metamorphosis represents academic attempts to pigeonhole and make sense of developments in this fast-paced technological development area. However, the omnipresent zeal for 'all things' CE adoption can obscure the main issues which must be tackled to improve its practical application in the construction sector (Kirchherr and Santen, 2019). To address this, undertaking a rigorous review and analysis of the study domain is paramount to effective and efficient adoption.

Existing review studies significantly contribute to the CE literature (Benachio *et al.*, 2020; Ciliberto *et al.*, 2021; Sparrevik *et al.*, 2021), but key limitations are also apparent. Most review studies focus on CE practices in the construction sector and omit any holistic contextualisation of CE practical applications in the built environment (i.e., what has been achieved and what else requires future investigation). For example, Benachio *et al.* (2020) conducted a literature review after collecting 45 construction articles on CE and focused on CE practices to only assess the project Life Cycle (LC). Sparrevik *et al.* (2021) focused their literature review on presenting different methods for assessing the built environment, including the life cycle perspective and the salvage value of asset's elements. In related research, Lovrenčić Butković *et al.* (2021) reviewed current assessment tools of CE projects applied to the construction industry, such as lifecycle assessment.

Norouzi *et al.* (2021) reviewed CE application areas in construction. Other review studies have focused on CE benefits and challenges. For instance, Hossain *et al.* (2020a) identified CE's implications, considerations, contributions, and challenges in the construction industry. They concluded that CE implementation is yet to be conducted and that a comprehensive CE integration and methodology framework requires development. Cruz Rios *et al.* (2021) identified the US's barriers and enablers to circular building design. Similarly, Shooshtarian *et al.* (2022) identified the main opportunities and barriers to minimise construction waste disposal through a review of 62 articles of Australian literature.

Several studies explored how building information modelling (BIM) could augment construction waste management (Akanbi *et al.*, 2019; Akinade and Oyedele, 2019b; Charef and Emmitt, 2021; Honic *et al.*, 2021; van den Berg *et al.*, 2020). Similarly, Charef and Emmitt (2021) proffer that BIM has the inherent potential to support CE implementation in disparate areas such as: sustainable end-of-life; material passport development; circularity assessment and material banks. Other scholars explored deep learning applications for demolition waste and reuse potential prediction of building's elements (Akanbi *et al.*, 2020a; Dong *et al.*, 2022; Rakhshan *et al.*, 2021; Xue *et al.*, 2021). Furthermore, blockchain potential as a CE enabler in the built environment was explored by Shojaei *et al.* (2021b). Deep learning was adopted to support CE in recycling and reusing material (Akanbi *et al.*, 2020a; Chu *et al.*, 2018; Rahman *et al.*, 2020). Other built environment applications include: Artificial intelligence (AI) with robotics for recycling management (Wilts *et al.*, 2021); and the Internet of Things (IoT) to predict the remaining lifetime of material and to classify household waste (Malapur and Pattanshetti, 2017; Rahman *et al.*, 2020; Sartipi, 2020; Wang *et al.*, 2021).

Research focusing on the practices of I4.0 applications and CE is scant. More research is needed to explore the potential of integrating various I4.0 technologies (i.e., IoT, blockchain, etc.) to foster CE adoption in construction. For example, Gupta et al. (Gupta *et al.*, 2021) identified the practices of I4.0, cleaner production and CE, but this review was limited to manufacturing organizations in an emerging economy context. Elsewhere Çetin *et al.* (2021) aimed to identify and map enabling digital technologies to facilitate a CE in the built environment but primarily focused on the enabling functionalities of the listed DTs rather than the implementation barriers in real-life practices. Dantas *et al.* (2021b) sought to link CE to I4.0 and elucidate how both can contribute to achieving sustainable development goals.

With all above in mind, this research critically analyses existing research that employs emerging digital technologies (such as blockchain, IoT and AI) to foster the adoption of CE in construction. To focus the analysis on the digital applications, a scientometric analysis is conducted to identify research clusters and then conduct a thematic-gap analysis to highlight the key papers' focus of study, employed methods and limitations. Sequentially, a conceptual framework is developed to show the usability of integrating various technologies over the asset lifecycle.

The rest of this paper is structured as follows: Section 2 presents the research methodology and econometric analysis, followed by CE and materials recycling prediction in Section 3. The analysis of the circular supply chain concept in construction is presented in Section 4. Section 5 includes the emerging digital technologies with CE. The barriers and enablers of CE are presented in Section 6, while Section 7 includes a discussion and the proposed conceptual framework. The practical implications and limitations are presented in section 8. Finally, the conclusion is presented in Section 9.

2. Methodology and Scientometric Analysis

Müller-Bloch and Kranz (2015); Rowe (2014) state that identifying the research gap is the main objective of reviewing literature in a specific subject rather than merely summarising past research findings. A mixed-methods systematic review (couched within inductive reasoning and an intelligent interpretive design) was adopted as such, is widely espoused as being the most effective epistemology (McGowan and Sampson, 2005). Utilising a mixed-methods systematic review is superior to mono method manual reviews (which can introduce researcher subjectivity and bias). It enables a more objective presentation of phenomena to be articulated. Moreover, a mixed-methods systematic review improves the depth and breadth of literature studied (Heyvaert *et al.*, 2016). Consequently, a scientometric analysis is conducted to measure the impact and density of publications (Rajendran *et al.*, 2011), for the CE-based emerging digital technologies and prevailing knowledge gaps. Figure 1 shows the process of data collection and analysis, specific keywords used included: ‘(circular AND economy AND digital AND technologies) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (EXACTKEYWORD , "Circular Economy") OR LIMIT-TO (EXACTKEYWORD , "Industry 4.0") OR LIMIT-TO (EXACTKEYWORD , "Sustainability") OR LIMIT-TO (EXACTKEYWORD , "Digital Technologies") OR LIMIT-TO (EXACTKEYWORD , "Sustainable Development") OR LIMIT-TO (EXACTKEYWORD , "Big Data") OR LIMIT-TO (EXACTKEYWORD , "Digitalization") OR LIMIT-TO (EXACTKEYWORD , "Industrial Economics") OR LIMIT-TO (EXACTKEYWORD , "Internet Of Things") OR LIMIT-TO (EXACTKEYWORD , "Artificial Intelligence") OR LIMIT-TO (EXACTKEYWORD , "Blockchain") OR LIMIT-TO (EXACTKEYWORD , "Digital Transformation") OR LIMIT-TO (EXACTKEYWORD , "Optimization") OR LIMIT-TO (EXACTKEYWORD , "BIM") OR LIMIT-TO (EXACTKEYWORD , "Circular Strategies") OR LIMIT-TO (EXACTKEYWORD , "Supply Chain Management") OR LIMIT-TO (EXACTKEYWORD , "Construction") OR LIMIT-TO (EXACTKEYWORD

, "Digital Manufacturing") OR LIMIT-TO (EXACTKEYWORD , "Economic System") OR LIMIT-TO (EXACTKEYWORD , "Digital Circular Economy") OR LIMIT-TO (EXACTKEYWORD , "Digital Mapping") OR LIMIT-TO (EXACTKEYWORD , "Digitalisation") OR LIMIT-TO (EXACTKEYWORD , "Ecosystems") . The results were refined according to the inclusion criteria, which includes (1) the relevance of the paper to the research scope, (2) the rank of the journal, only ranked Q1 and Q2 journals on scopus were considered, (3) the publication date (from 2015 to 2021). After that, a conceptual framework is developed to integrate various emerging technologies to enable CE for existing/new smart cities.

Table 1 shows that the progress of publication for CE-based emerging digital technologies from 2015 top 2021 and illustrates a sharp increase in publications from 2019.

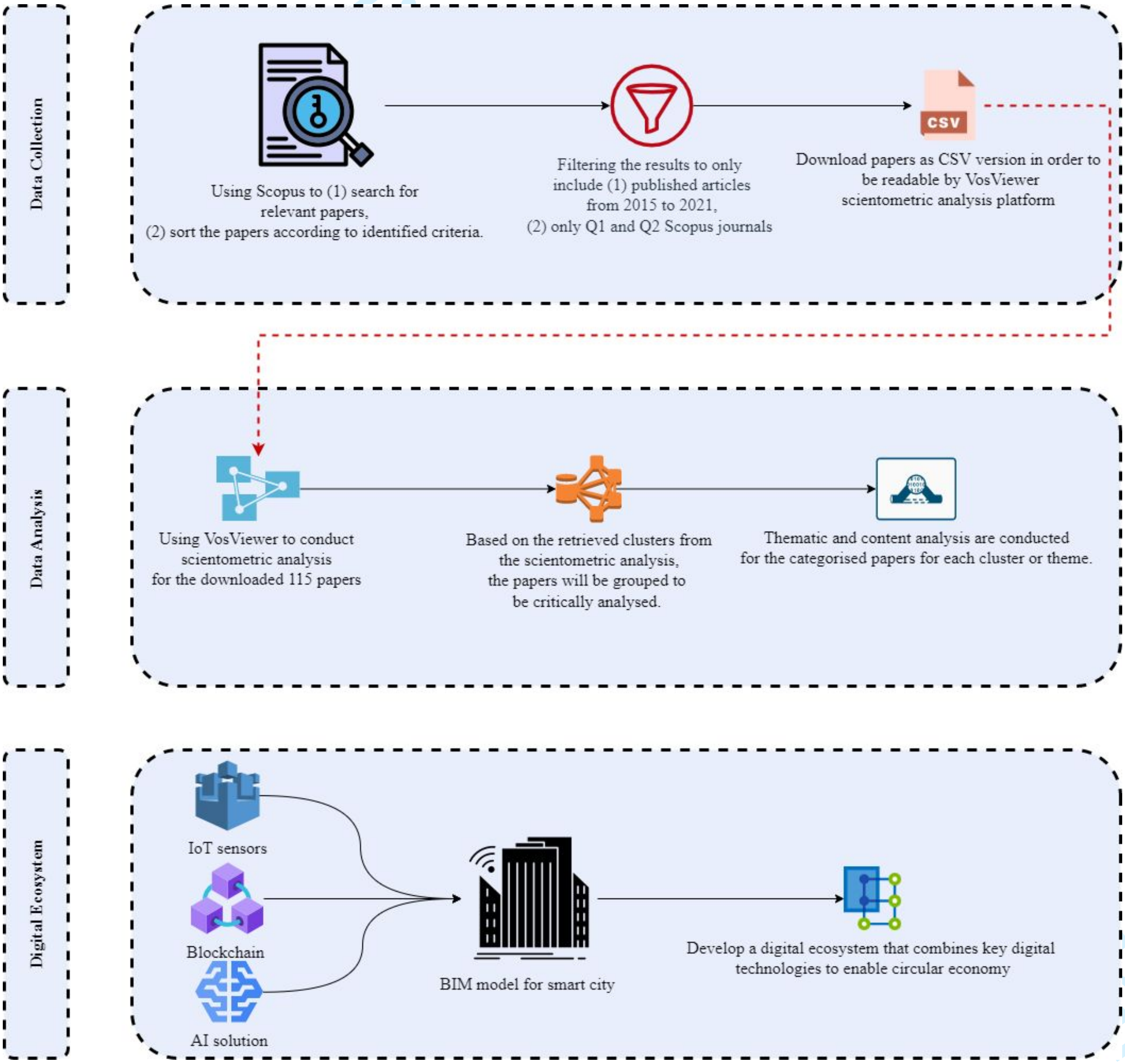

Figure 1. Research methods and logic

Table1. Publication per year for CE-based emerging digital technology

Year	Documents	Accumulative frequency	Percentage growth
2015	1	1	0
2016	1	2	0.9
2017	3	5	2.6
2018	9	14	7.8
2019	15	29	13.0
2020	35	64	30.4
2021	51	115	44.3

Table 2 shows the geographical allocation of publications and indicates that the UK has the highest number of publications over the last seven years (2015-2021), and France has the lowest number of publications.

Table 2. The geographical analysis of publication from 2015 to 2021

Countries	Frequent count	% of the whole for each country	prominent authors (having more than two papers)
United Kingdom	23	13.2	Oyedele, L.O.; Akanbi, L.A.; Akinade, O.O.; Bilal, M.; Charef, R.; Davila Delgado, J.M.; Emmitt, S.; Abdel-Basset, M.; Abrishami, S.; Ajayi, A.
United States	14	8.0	Kim, K.; Cho, Y.K.; Cruz Rios, F.; Grau, D.; Ahn, C.R.; Ayer, S.; Bai, Y.; Baker, H.; Bertino, E.; Bilec, M.
China	13	7.5	Ghisellini, P.; Li, C.Z.; Li, M.; Li, P.; Lin, X.; Shen, J.; Ulgiati, S.; Wu, H.; Xiong, X.; Albertí, J.
Netherlands	12	6.9	Adriaanse, A.; Bocken, N.; Voordijk, H.; van den Berg, M.; Çetin, S.; Ahmadi, H.B.; Allen, S.; Balkenende, A.R.; Bocken, N.M.P.; Brown, P.
Spain	12	6.9	Aguayo-González, F.; Llena-Macarulla, F.; Martín-Gómez, A.; Ávila-Gutiérrez, M.J.; Albertí, J.; Aranda; Usón, A.; Assiego, R.; Azapagic, A.; Boer, D.; Bonoli, A
Italy	11	6.3	Ghisellini, P.; Ulgiati, S.; Acampora, A.; Adelfio, L.; Angrisano, M.; Boer, D.; Bonoli, A.; Borg, R.P.’; Cabeza, L.F.; Cedillo-González, E.I.

Australia	9	5.2	Abdel-Basset, M.; Akanbi, L.A.; Ali, S.M.; Bilal, M.; Chakrabortty, R.K.; Chang, V.; Colling, M.; Gruner, R.L.; Hawash, H.; He, P.
Canada	8	4.6	Haas, C.; Sanchez, B.; Ahmad, R.
Hong Kong	8	4.6	Hossain, M.U.; Li, C.Z.; Li, M.; Lin, X.; Ng, S.T.; Wu, H.
France	5	2.9	N/A
Others	59	33.9	

Table 3 shows the analysis of citations and collaboration among authors of 115 papers. Analysis reveals that the average citations per document are 24.31, reflecting good publication progress regarding emerging technologies with CE. Regarding authorship analysis, the average per document is 3.44, and the collaboration index is 3.46, indicating that researchers are constantly working to develop solutions for CE-based emerging technologies (see table 3).

Table 3. Authorship analysis

Description	Results
Average citations per document	24.31
Average citations per year per doc	6.228
Documents per Author	0.291
Authors per Document	3.44
Co-Authors per Documents	3.84
Collaboration Index	3.46

The scientometric analysis is conducted for 115 papers. The analysis is configured using the occurrences analysis method to show the density of publications in the concepts related to CE-based emerging digital technology. Four thematic clusters are apparent, namely: (1) Life Cycle Assessment (LCA), (2) decision-making tools, (3) two clusters related to AI, (4) IoT, and other technologies applications for circular supply chain and waste management. Figure 2 shows growth in employing emerging technologies to leverage CE for the built environment sector. However, the relationship is not strong among different emerging technologies, which indicates that further studies are required that integrate technologies such as AI, IoT, blockchain, etc. to foster CE adoption in the whole life cycle of buildings.

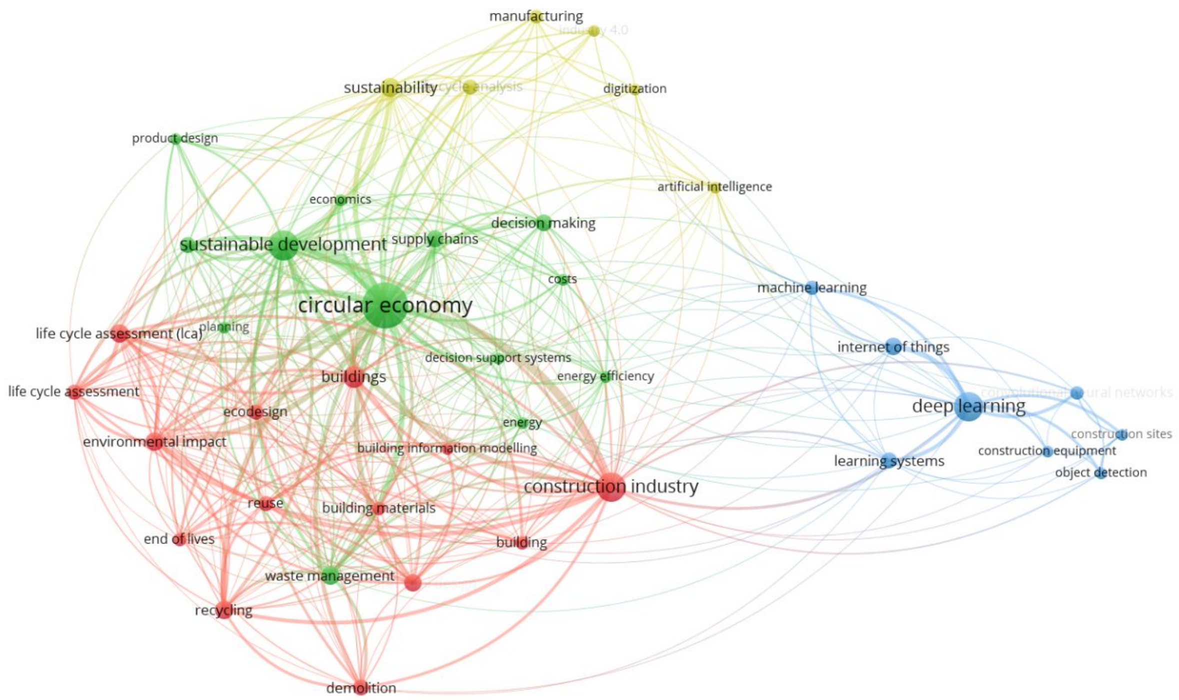

Figure 2. Scientometric analysis of CE-based emerging technologies publications

3. Circular Economy and Materials Recycling Prediction

The CE concept started with various stakeholders' attempts to reduce anthropogenic environmental impacts (Desing *et al.*, 2020). Given limited resources and energy, scholars agree that it is vital to ensure sustainable resource management, thus reducing entropy production, increasing materials' durability, and enhancing processes' efficiency (Desing *et al.*, 2020). Recently, several scholars have investigated CE as an enabler to sustainable development (Borg *et al.*, 2021; Camana *et al.*, 2021; Dantas *et al.*, 2021a). Some studies explored material and design efficiency in terms of reuse and recycling (Borg *et al.*, 2021; Honic *et al.*, 2021; Karakutuk *et al.*, 2021; Rakhshan *et al.*, 2021; Sanchez *et al.*, 2019). Several studies conducted consider the material passports (MP) method for construction materials. For example, Honic *et al.* (2021) estimated the total potential masses of reusable, recycled exterior walls and the foundation materials and the environmental impacts to support circularity and sustainability in the construction sector. Karakutuk *et al.* (2021) solved a real-life design problem using a mathematical programming model while considering cost minimization and saving maximization. This solution provides different design configurations to the decision-maker, thus affording applications in designing energy-efficient production systems.

Other researchers investigated the possibility of replacing construction materials with other more sustainable materials to reduce the environmental impact of the construction industry. For example, La Scalia *et al.* (2021) investigated the industrial process to produce Geopolymers (GP) to replace Ordinary Portland Cement (OPC) and, in so doing, significantly reduce CO_2 omissions. The authors (*ibid*) concluded that a waste-based GP product engenders noticeable energy savings and a decreasing cost per ton, increasing waste recycling. Similarly, Borg *et al.* (2021) assessed the performance of recycled ultra-high durability concrete (R-UHDC) as a substitute for natural aggregate to enhance the environmental impact of cementitious products further. Salem *et al.* (2020) investigated the performance of mortar containing industrial waste (i.e., synthetic vegetable sponges) as natural sand replacement.

Dams *et al.* (2021) developed a circular construction evaluation framework (CCEF) that can quantify the level of circularity in a construction project using criteria specified in an accessible tabulated format. Ghaffar *et al.* (2020) surveyed the UK construction industry to analyse the current barriers of C&DW management from the demolition sector's perspective and revealed that components' reuse could be improved if smart demolition and selective dismantling are implemented. van den Berg *et al.* (2020) concurred and applied a fieldwork-based approach to establish a proposition for cleaner demolition processes viz: the demolition contractor (1) identifying an economic demand for the element(s); (2) distinguishing appropriate routines to disassemble it; and (3) controlling the performance until integration into a new building. Sanchez *et al.* (2019) demonstrated the affordability and practicality of using selective deconstruction programming for adaptive reuse projects by using current technologies such as 6D BIM, disassembly planning optimization models and PM software. Table 4 shows key published articles regarding estimating the recyclable waste for construction materials.

Table 4. Evaluating recyclable materials key published papers

Author/Year	Focus of study	Methods	Limitation
Borg *et al.* (2021)	This study aimed to assess the performance of recycled ultra-high durability concrete (R-UHDC) as a substitute for the natural aggregate.	Using a cradle-to-cradle approach.	All the samples containing recycled aggregates feature a higher peak in correspondence with the temperature of the carbonate phase decomposition.
Dams *et al.* (2021)	This study aimed to assess and quantify the circularity credentials of an existing or proposed construction project.	By developing a free-to-use Circular Construction Evaluation Framework (CCEF) based upon international design code guidelines.	The developed framework utilises the guidance in BS ISO 20887:2020 as a basis for adaptation.

Honic *et al.* (2021)	This study aimed to appraise the recycling potential and environmental impact of materials embedded in buildings.	Applying the material passports method using three acquisition methods: laser scanning, demolition acquisition (DA) and Urban Mining assessment (UMA),	The reuse or deconstruction potential as well as the location of a material within the building is not considered in this study. Thus, the method requires some refinement.
Mutezo and Mulopo (2021)	This study aimed to explore the Big Five's transition from fossil fuel to renewable energy and assess whether the transition can be enabled and guided by the principles of a CE.	Using a systematic literature review process.	The context of the study is limited to Africa.
Rakhshan *et al.* (2021)	This study aimed to develop a probabilistic model to predict the reuse potential of structural elements at the end-of-life of a building.	Using advanced supervised machine learning techniques (including random forest, K-Nearest Neighbours algorithm, Gaussian process and support vector machine).	The low rate of reuse in the building sector that restricts access to more experts with such experience.
van den Berg *et al.* (2021)	This study aimed to investigate how deconstruction practices can be changed with BIM.	By applying an activity-theoretical perspective to a case-study.	This study cannot answer whether the resolved contradictions outweigh the emerging new ones.
Akanbi *et al.* (2020a)	This study aimed to estimate the materials output from buildings based on the basic features of the building.	Using deep learning models.	The deep learning models developed are based on dataset contains information about the UK building stock only.
van den Berg *et al.* (2020)	This study aimed to understand the (socio-technical) conditions which lead to the recovery of a building element for reuse.	Using Mixed-method approach of participant observations with semi-structured interviews and project documentation.	The context of study is limited to the Netherlands.
Eray *et al.* (2019)	This study aimed to demonstrate how the Interface Management System (IMS) could eliminate most of the barriers on the adaptive reuse projects.	Through an extensive literature review and case study.	The interface system was developed and validated based on one case study in Canada.
Sanchez and Haas (2018b)	This study aimed to develop a single-target selective disassembly sequence planning method to minimize environmental impact and removal costs of existing buildings. .	Using rule-based recursive analyses	The developed method incorporated only a single method of disassembly or deconstruction.

4. Circular Supply Chain for Construction Industry

The field of supply chain management and CE in the construction industry has attracted research to establish a possible strategy through business model innovation, focused on solving environmental, social and economic related issues (Korhonen *et al.*, 2018). For example, Leising *et al.* (2018) explored how new approaches to supply chain collaboration can support the transition to a circular building sector in the Netherlands and developed a novel framework of supply chain collaboration with CE. De Angelis *et al.* (2018) investigated the links between CE and supply chain management and discussed the key supply chain challenges facing managers, namely: extending the shifting perceptions of value; mitigating risk through structural flexibility; introducing early supplier innovation; increasing strategic services; and addressing the issue of global vs local distribution of production.

Akinade and Oyedele (2019a) developed a hybrid BIM-based computational tool for building waste analytics and reporting in construction supply chains. This solution is integrated as an add-in for Autodesk Revit (Bressanelli *et al.*, 2019). The authors (*ibid*) suggested that a great degree of vertical integration by one actor in the supply chain is not crucial for CE implementation.

Bressanelli *et al.* (2021) recommend that policy-makers should advance mandatory regulations to push circular product design (such as Ecodesign directives) and to clearly delineate the roles and obligations of each stakeholder in the electrical and electronic equipment supply chain. Haleem *et al.* (2021) identified criteria for supplier selection according to their relevance to the CE based on an extensive literature review and qualitative data from industry experts. Dulia *et al.* (2021) developed a framework using the fuzzy synthetic evaluation approach to assess risks for increasing the industry's circular supply chain effectiveness. Table 5 shows the key published studies for the circular supply chain.

Table 5: CE and supply chain management

Author/Year	**Focus of study**	**Methods**	**Limitation**
Dulia *et al.* (2021)	This study aimed to assess the risks for increasing the circular supply chain effectiveness in the industry.	Using fuzzy synthetic evaluation approach	Sample size was not large.
Haleem *et al.* (2021)	The study aimed to develop a framework for evaluating the supplier	Using the fuzzy CRITIC and fuzzy TOPSIS techniques.	The lack of experts in the field of supply chain and CE.

	concerning the CE implementation.		
Akinade and Oyedele (2019a)	This study aimed to present how supply chains integration with BIM are critical for construction waste management.	Using a hybrid system known as ANFIS, which combines the strengths of fuzzy systems and ANN.	The study was carried out within the UK construction industry context, so the findings have a UK bias.
Bressanelli *et al.* (2019)	This study aimed to identify 24 challenges that may hinder the supply chain redesign for the CE.	Through a systematic literature review and case analyses.	The four case studies have been selected for their suitability, rather than for representativeness
De Angelis *et al.* (2018)	This study aimed to define circular supply chains and the embodiment of CE principles within supply chain management.	Through a systematic literature review.	Very little information on the practical side of how to introduce circular supply chain in a real-world context.
Leising *et al.* (2018)	This study aimed to explore how new approaches of supply chain collaboration can support the transition to a circular building sector in the Netherlands.	By investigating three cases using the developed framework.	It should be noted that only three cases were studied.

5. Circular Economy and Emerging Digital Technologies

a. Circular Economy and Blockchain

The synergies between the CE concept and blockchain have received significant attention from researchers in recent years. For example, Upadhyay *et al.* (2021) studied the implications of employing blockchain to achieve sustainability goals: minimising transaction cost; enhancing the trust among industry parties; and providing a secure communication environment for interconnected supply chain processes. These tangible benefits of blockchain to foster the adoption of the CE concept have been extensively verified Böckel *et al.* (2021). There are practical applications of implementing blockchain and multi-sensor-driven AI for CE. For example, Chidepatil *et al.* (2020) traced plastic waste. They managed the supply chain tasks, including purchasing, carrying and inventory tasks using blockchain smart contracts to speed the processing of plastic waste. Integrating products and services in an interconnected process using blockchain can enable to estimation the product lifecycle (Gharaibeh *et al.*, 2022; Kouhizadeh *et al.*, 2019; Vogel *et al.*, 2019). Reserve logistics (RL) is a vital dimension in the CE process; therefore, Bekrar *et al.* (2021) proposed a nexus of transportation, RL and blockchain to digitize the operation of the transportation equipment reserve supply chain. This allowed automatically tracking all equipment components using an immutable ledge blockchain feature to acquire an accurate reserve supply chain system.

Directly implementing blockchain to achieve CE for the construction industry is presented by Shojaei *et al.* (2021a), who revealed that blockchain allows practitioners to trace and predict material values and energy consumption throughout the project and asset lifecycle. This enables designers to optimize the design to use materials with inherently high salvage value by the end of a building's lifetime (Shojaei *et al.*, 2021a). Furthermore, blockchain can also be employed in large scale projects to track the value of assets throughout an operation lifecycle. This can be achieved by giving an ID for each facility and enabling parties (public) to invoke transactions to change the values of their assets regularly. Therefore authorities can obtain a precise value of all assets (Maciel, 2020). Moreover, blockchain is a prominent tool to support the transition to green energy through using automated and digital measurement, reporting and verification (MRV) systems to track energy consumption and enable the building sector to contribute to the carbon credit market (Woo *et al.*, 2021).

Blockchain has been utilised to develop a collaborative construction design platform to automatically track changes, enabling a wide range of stakeholders to provide views towards sustainable design (Nawari and Ravindran, 2019; Singh and Ashuri, 2019). Davidova and McMeel (2020) developed a 'Synergetic Landscapes'-based blockchain to enhance urban design by developing a system that considers the design's living, non-living, physical, analogue, digital and virtual aspects. This process is implemented by representing design factors as tokens and enabling all stakeholders to share their contributions through a blockchain network (Davidova and McMeel, 2020). Li and Kassem (2021) state that integrating blockchain, BIM, and IoT allows two-way communication from the built asset to the BIM model and vice-versa. However, a digital ecosystem is required to integrate all these technologies properly. Given, that the CE concept is more considered in modern smart cities (and the development of such cities requires an automated linkage among all assets), IoT and blockchain should be integrated to enable fine-grained and continuous asset tracking (Damianou *et al.*, 2019; Elghaish *et al.*, 2021a; Rahimian *et al.*, 2021).

Shojaei *et al.* (2021a) investigated the comprehensive advantages of CE-based blockchain for the built environment sector, and findings show that blockchain can trace the construction materials from source to end of useful life, which maximize the opportunity of early planning of reuse to eliminate wastage. However, all proposed construction CE solution-based blockchain should be extended by providing workable and practical solutions that work for large-scale projects.

b. Circular Economy and Artificial Intelligence

Sepasgozar (2021) asserts that the construction industry generates around 50% of carbon emissions and consumed energy. Therefore, enhancing productivity through employing emerging technologies can significantly reduce carbon emissions and energy consumption. In related research, Chehri and Saeidi (2021) and Elghaish *et al.* (2021c) proposed the integration of IoT and deep learning to detect the deterioration of structural health for bridges' elements due to the environmental causes, which can increase the operating lifetime of these elements. Enabling CE requires continuous data collection and a deep data analysis tool therefore, Ramadoss *et al.* (2018) developed a framework to employ low-cost sensors in re-usable products/devices to collect data and use AI to analyse these data. Therefore, re-usable materials can be detected and subsequently used for new developments.

Even though different forms of AI adopted (mechanical, analytical and intuitive) to manage the reserve supply chain have received significant academic attention, an entrepreneurial ecosystem is needed to leverage its adoption for a large-scale application (Wilson *et al.*, 2021). A case study conducted by Wilts *et al.* (2021) utilised AI with a robotic sorting system to sort bulky municipal material waste. The results (*ibid*) showed that the recovered materials' recycling rate and purity were increased, and labour working conditions were enhanced. The automatic and self-management of waste-based deep learning can classify and sort materials with a reliability percentage of 90% to 100% for reusable material (i.e., organic materials); such can significantly reduce the cost and maximize the value of recycling a wide range of materials (Nañez Alonso *et al.*, 2021).

Akanbi *et al.* (2020b) proposed a deep learning model to estimate the salvage value of building materials before demolition, which supports decision-makers to determine the monetary value of materials to be recovered. The same concept was introduced as a large scale application to use a multilayer hybrid deep-learning system (MHS) to detect and estimate waste generated within public areas using a high-resolution camera (Chu *et al.*, 2018). However, instead of employing a high-resolution camera, IoT, in conjunction with deep learning, can be used to collect and analyse real-time waste data (Rahman *et al.*, 2020). This concept is widely implemented in modern smart cities to share data among truck drivers on real-time waste collection and optimized distances to the waste site (Elghaish *et al.*, 2021b; Malapur and Pattanshetti, 2017; Medvedev *et al.*, 2015). Moreover, IoT enables household waste to be automatically classified to avoid householders' bad behaviours, such as mixing metal and plastic trashes with non-recyclable items (Wang *et al.*, 2021).

IoT can be employed to predict the remaining lifetime of materials to optimize the reuse of these materials or extend their operational lifetime (Ingemarsdotter *et al.*, 2020). Sartipi (2020) assert that 5G, IoT and deep learning can revolutionize the entire construction process towards the adoption of CE in terms of automating the control of carrying materials and collecting and analysing different types of waste during construction.

c. Circular Economy with Construction 4.0

The terms of CE and I4.0 have often appeared together, for example, Benachio *et al.* (2020); Martínez-Rocamora *et al.* (2021); Nascimento *et al.* (2019); Piscitelli *et al.* (2020); Rajput and Singh (2019); Sanchez and Haas (2018a) and Rahimian *et al.* (2021). This indicates that the interrelationship between their processes and tasks is very strong. Furthermore, the common area between their applications should be critically analysed, given I4.0 advanced technologies can significantly support the circularity of resources (Piscitelli *et al.*, 2020).

Martínez-Rocamora *et al.* (2021) introduced a methodological-technological framework based on I4.0 technologies to enable the construction CE process. Different business and technical models were developed by Rahimian *et al.* (2021) to implement I4.0 technologies such as blockchain, IoT, AI and drones to minimize fragmentation in construction and adopt a circular supply chain. However, further validation is required using large scale case studies to check the scalability of proposed solutions. Therefore, to invest in reverse logistics in construction, lean design and production concepts and methodologies should be employed using I4.0 technologies (Ciliberto *et al.*, 2021).

Additive manufacturing plays an important role to utilize resources efficiently in construction. However, this requires integrating different construction 4.0 technologies such as 3D printing (i.e., additive manufacturing) and IoT (Craveiroa *et al.*, 2019). Despite the potential of 3D printing to efficiently utilize resources, there is a challenge in terms of comparing the durability of materials and the technology cost for large-scale application (Sauerwein *et al.*, 2019). Moreover, Ashima *et al.* (2021) assert that employing IoT with additive manufacturing can significantly reduce waste and make the process and application of additive manufacturing customer-friendly. On the other hand, construction 4.0 requires an intelligent production system to enable a flexible and automated production system for custom-design products (Suresh *et al.*, 2020). Salama *et al.* (2018) proposed utilising The Industrial Internet of Things (IIoT) to allow the real-time monitoring of the fabrication process of construction elements in the factory.

Digital Twin (as a replica of the physical building) is also proposed to be utilised to improve the remanufacturing process, including tracking, recycling and managing construction wastes to enter the remanufacturing process (Chen and Huang, 2020). However, a Digital Twin application for construction CE requires developing a workable solution to track the performance of a wide range of materials and services from assets and link this data with the information model (Boje *et al.*, 2020; Lu *et al.*, 2020). Hence, Tagliabue *et al.* (2021) applied Digital Twin in conjunction with IoT to assess the sustainability factors for an educational building through its whole life cycle. The findings (*ibid*) show that Digital Twin and IoT enable better real-time sustainability evaluation, contrary to the traditional check-listed approach adopted by sustainability rating protocols. From building scale to smart cities, Hämäläinen (2020) recommended the employment of Dynamic Digital Twin (DDT) to track smart cities' buildings and services performances, then automatically detecting and managing the reuse of elements after the lifetime comes to an end. Utilization of Digital Twin and IoT can minimize the supply chain lead time toward developing a lean, flexible and smart supply chain 4.0 system (Abideen *et al.*, 2021). There are a few attempts to develop integrated platforms. For example, Kovacic *et al.* (2020) proposed a digital platform for construction CE that enables all stakeholders to manage building construction and operation resources from a CE cradle-to-grave perspective.

6. Key Published Research to List Barriers and Enablers

Several studies focused on identifying barriers and enablers for CE strategies in the built environment (Charef and Lu, 2021; Cruz Rios *et al.*, 2021; Kanters, 2020; Mahpour, 2018; Rakhshan *et al.*, 2020). Mahpour (2018) identified 22 potential barriers to transition to CE in construction and demolition waste management. The barriers are prioritized aggregately and based on individual perspectives using the fuzzy TOPSIS method. Rakhshan *et al.* (2020) reviewed methods to identify, categorize and prioritize drivers and barriers affecting the reuse of building components on a global scale. The key revealed challenges in this study were triggered due to economic issues.

Several recent empirical studies have analysed barriers and enablers using research strategies such as case studies, interviews, surveys and focus groups. For example, after interviewing twenty European experts in the field, Charef and Lu (2021) identified 64 factors impacting CE adoption and placed them into three related categories: organisational, political and procedural, and technical factors. By using a pattern-matching method, some authors presented the socio-economic and environmental barriers for a holistic view of the asset lifecycle in the context of CE. Kanters (2020) interviewed twelve architects and consultants to gain insight into successful circular building design processes and identify barriers and drivers for the transformation to a more circular building sector. Barriers found (*ibid*) included the conservative nature of the construction sector, the cost of labour, and the need for flexibility in existing building codes and regulations.

Conversely, the main enabler was a supportive client. Akinade *et al.* (2020) conducted focus groups. They added several new barriers to the literature, most related to circular building design tools and clarified that there is a: lack of tools for identifying and classifying salvaged materials; lack of performance analysis tools for evaluating end-of-life scenarios of buildings; and limited visualization capability for design for deconstruction (DfD) in building information modelling (BIM). Most of these empirical studies identify barriers to circular building design in European countries. However, given the different regulatory, economic and cultural contexts in other countries, Cruz Rios *et al.* (2021) interviewed 13 architects across the US to understand the perceived and experienced barriers to circular building design, such as ignoring reusing salvaged materials in new designs, an underdeveloped marker for salvaged materials and lack of standardization and transportability of building components. This study also proposed enablers to overcome these barriers such as: 'integrating CE in contractual requirements for design'; 'creating databases for reusable components; 'urban mining' and 'integrating CE strategies to ICT'. The barriers differed in nature from those found in European countries: although technical and economic barriers were similar, more educational and cultural barriers were found in the US (e.g., lack of stakeholders' knowledge and awareness of CE strategies and benefits and lack of public awareness on life cycle costs and benefits) as opposed to a greater share of regulatory and technological barriers in European countries (e.g., existing regulations and codes hinder reuse and repair, lack of data about availability, quality, and quantity of salvaged building components). The literature review revealed that the main barriers to realising CE in construction are: (1) the time and labour-intensive nature of deconstruction increases the project costs and delays the schedule (Hossain and Ng, 2018; Rakhshan *et al.*, 2020); (2) the high initial investment (Cruz Rios *et al.*, 2021; Hossain *et al.*, 2020b; Rakhshan *et al.*, 2020); (3) regulatory barriers (Akinade *et al.*, 2020; Kanters, 2020; Rakhshan *et al.*, 2020); legislation by the Government on the reuse and recycling threshold (Ghaffar *et al.*, 2020); and management problems related project organization structures of the stakeholders (Eray *et al.*, 2019).

7. Discussion on Findings and conceptual framework

This paper presents a vignette of the current status of integrating emerging technologies into CE to foster the adoption of its concepts, processes and techniques in the construction industry. The current synergies between sustainability and CE concepts are investigated, and findings indicate that considering the circular supply chain concept for construction assets enables decision-makers to involve reusable materials for the new design development. One workable solution for this purpose is the circular construction evaluation framework (CCEF), as developed by Dams *et al.* (2021), which can quantify the circularity of materials entered into new buildings. Hence, the new design should include these materials to minimise waste and increase the salvage value. Furthermore, the research to integrate sustainability and CE is also extended to consider smart demolition, such as the system developed by van den Berg *et al.* (2020) to determine the best way to disassemble building elements and optimise performance; therefore, valid elements can be used for the reverse supply chain process.

Even though LCA calculations are traditionally conducted to estimate the entire building life cycle cost, the concept of CE enhanced the utilisation of LCA in construction through (1) utilising BIM to build energy simulation to estimate the operating cost precisely over the asset's life cycle; (2) developing a set of circular design alternatives-based LCA and rank these alternatives; and (3) estimating the embodied carbon in the design element-based BIM, as well as using digital twin to track and update LCA during the asset operation stage.

The supply chain plays a vital role in implementing CE, and a plethora of research recommends utilising emerging technologies, particularly blockchain and IoT, to enhance the reverse supply chain process. Currently, there are some attempts to develop an innovative business model to involve suppliers early, mitigate risks in supply chain tasks through structural flexibility, and encourage a set of regulations and standards to force circular design practices among producers and provide a new tender selection approach-based sustainability factor. However, despite the noticeable growth of research into circular supply chain management, more practical solutions are still required to facilitate the adoption of circular and functional supply chains in the construction industry.

This research indicates that emerging technologies such as blockchain, IoT, AI and digital twin have a prominent role in leveraging the CE for the construction industry. Various applications either employ one of these technologies in isolation or integrate several in coalescence to leverage their capabilities.

Blockchain can play a significant role to trace the supply chain elements over the project and asset lifecycles, which is the main step toward a circular supply chain. However, most research on blockchain-based CE is conducted for different engineering sectors, and the construction/built environment remains scant (Shojaei *et al.*, 2021a). Real-time data collection is essential to track the performance of assets' elements. Therefore, several research projects employed IoT sensors to collect real-time data. Applications included construction waste or checking the performance of assets' services or elements to conduct maintenance or replacement at the right time to extend the lifetime of asset operation.

The coupling of IoT and BIM is introduced to provide digital twin platforms that can efficiently leverage the Asset Information Model (AIM) during the asset's operation lifetime (Chen and Huang, 2020; Hämäläinen, 2020; Lu *et al.*, 2020). However, most existing solutions are mainly designed for new smart cities. Therefore, solutions are needed to integrate IoT technology into existing buildings and enable tracking salvage value of buildings over time. Moreover, a digital ecosystem is required to combine all mentioned technologies and automate the entire process, which minimises the required human interaction to enhance data collection and processing accuracy. AI, particularly deep learning subset, is recommended by many studies such as Jose *et al.* (2020); Liu and Jiang (2021); Ramadoss *et al.* (2018); Wilson *et al.* (2021) to automate the process of design regarding developing optimised and CE design alternatives. Such alternatives include sustainable materials, lower energy consumption design and considering reserve logistics of construction materials.

Based on existing research, figure 3 shows the proposed conceptual framework encompassing key emerging technologies such as AI, blockchain and IIoT. The number of IIoT sensors utilised has increased to detect comprehensive information such as labour detection sensors, carbon emission sensors, and environmental sensors. Therefore, a wide range of sensors can be employed to collect real-time information regarding data about the structural health of buildings, carbon emission quantities, energy consumption patterns etc. The collected data can be stored in a blockchain platform (i.e., Hyperledger fabric). There should be a smart contract that includes different functions to restore all types of information to enable decision makers to make the right decision on the right time. IoT sensors will enable automatic 'real-time' distribution of information to the blockchain network to augment decision making over the asset's lifecycle. AI can be used to analyse collected data from IIoT sensors. Particularly, deep learning models can be developed to detect and evaluate the functionality and validity status of a building's structural, mechanical and electrical elements to enable asset operators to make the right decision in terms of maintenance or replacement. An interactive monitor should be connected to IIoT sensors to enable asset operators to monitor building performance and display the outcome of deep learning analysis. Moreover, the asset's operators can also record their decisions, such as replacing/upgrading asset services or elements in the blockchain network to enable different users to track all changes in the asset over the entire lifecycle. Most studies confirmed that integrating IoT sensors into the BIM process will enable developing a reliable AIM that operators can use to evaluate the performance of all services and reflect this on the new design developments to avoid deficiencies on existing services.

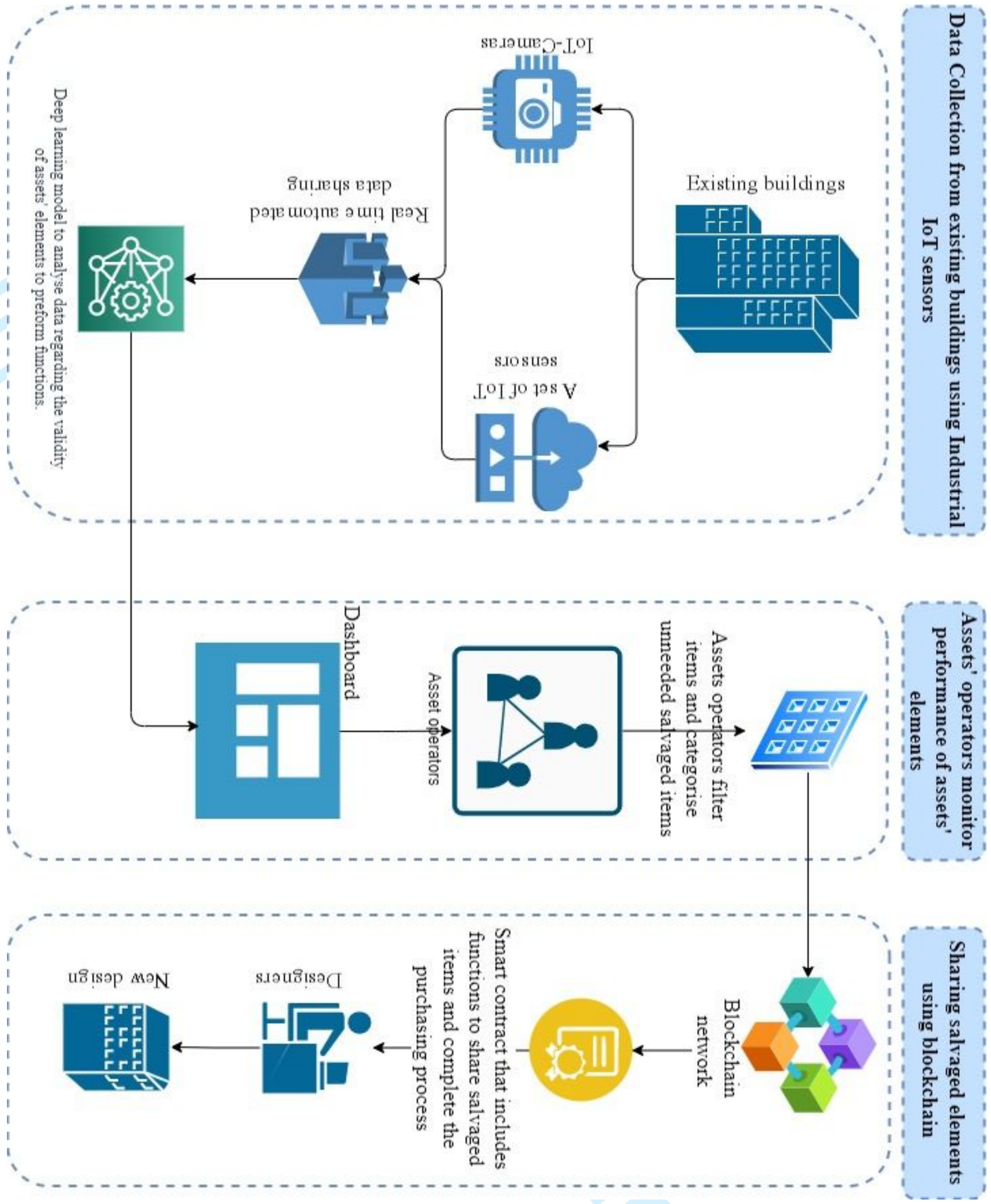

Figure 3. IoT, blockchain and BIM for circular supply chain for existing buildings

8. Practical implications and limitation

This research has a wide range of practical implications to foster the adoption of circular supply chain in the construction industry as follows:

- The outcome of the paper could enable researchers to develop practical blockchain , IoT and AI solutions to trak and analyse resources over the asset lifecycle.
- The created conceptual framework raises the awareness of integrating different digital technologies in an integrated platform to attan the circular economy in the construction industry.
- This paper works as a point of departure for novice researchers to find the knowledge and practical gaps in existing research.

Even though this research analysed key published research regarding employing digital technologies to attain circular supply chain in the construction industry, however, the proposed solution is conceptual and ‘Proof of Concept’ needs to be developed to test the validity, applicability and workability of the proposed solution.

9. Conclusion

This paper introduces a comprehensive and critical overview of employing emerging technology to adopt CE in construction. The paper began by exploring the interrelationships between sustainability and CE from a state-of-the-art review. Findings infer a strong link between the consideration of sustainability level in the design and construction process via the adoption of CE's concept, tools, and construction practices.

Emerging technologies play a vital role in achieving the desired level of the circular supply chain, which is fundamental to moving toward an integrated circular construction economy. Blockchain in integration with IoT can provide a secure and interconnected platform to track the element supply chain over the project’s and asset’s lifecycle. However, most existing research provides conceptual solutions and a digital ecosystem. Therefore, there is a need for more workable solutions that can be validated using real-life case studies. Findings also indicate that other digital technologies such as AI are currently employed to automate developing design alternatives that embed CE practices for construction and operation stages.

In addition to studying the role of emerging technologies to foster CE adoption (particularly, circular supply chain in the construction industry), this study also investigated the main barriers and opportunities to leverage CE in construction. The findings indicate that the main barriers are: (1) a fragmented and costly method of demolition; (2) the required capital investment to adopt CE; (3) a lack in the existing regulations to motivate construction societies over the world; (4) the difficulties in estimating the salvage value of building elements. The analysis of 115 papers indicated that most of the research focused on integrating the CE concept into designing and constructing new smart cities. However, there is a high need for more research to implement the CE concept for existing buildings/cities. This will enhance buildings’ performance in terms of energy consumption, the supply chain for replacement/maintenance of building elements and extending the working life of buildings.

In addition to critically analysing existing solutions of emerging technologies for construction CE, this paper provides a conceptual model to integrate blockchain and IoT sensors to track building elements and services such as energy consumption rates, carbon emissions and 'heating and cooling systems' during the operation stage. The proposed conceptual integration model can be extended in future research to implement in real case studies and measure its validity and workability under different operational situations.

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