Key approaches to construction circularity: a systematic review of the current state and future opportunities

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Abstract –

Circular economy (CE) strategies have been considered to help reduce global sustainability pressures in different sectors; however, there is a gap about how they could be used to contribute to the Architectural, Engineering and Construction (AEC) domain. Past research used lifecycle assessment (LCA) methods or experts' opinions to partially identify the benefits and drawbacks of specific CE strategies or approaches adopted in construction projects. This study presents a systematic literature review to identify the scope of key approaches to construction circularity. From a rigorous selection and review of 40 journal articles, this study identifies 15 key approaches that emerged from the state-of-the-art. These approaches represent the efforts of using digital technologies, comprehensive mapping and assessment methods, and material experiments to allow construction circularity from 5 different perspectives: material design, building design, construction and facility management, urban sustainability development, and system precondition, which emphasize the communication between project stakeholders concerning what, how and when the materials should be used within the estimated number of life cycles. Findings reveal the importance of integrating the stakeholders, service centers and recycling plants, transportation networks, and local authorities to work together to deliver construction circularity at micro, meso, and macro levels. The legal, risk, financial (funding and taxes), and contractual frameworks need to be further studied to fully explore the different opportunities of circular strategies and approaches in the AEC domain.

Keywords –

Circular economy; Construction circularity; Sustainability; Digital enablers; Reuse and recycle

1 Introduction

The AEC industry is one of the most resource-intensive ones. It is responsible for 35 % of all solid waste and 42% of primary energy demand in Europe [1]. The concept of circular economy (CE) (slowing, narrowing, and closing resource flows) [2] and associated strategies help stakeholders redefine the workflows in the industry towards sustainable projects in terms of reduced greenhouse gas emissions and minimized resource use. Understanding the CE strategies used in the AEC domain is not easy, especially considering construction projects' high complexity and uncertainty nature. However, the term "circular buildings" or "construction circularity" received increasing attention in recent years [3]. There has been no standardized way of defining and evaluating construction circularity as circularity encompasses every possible interaction and process related to a given material from material extraction to project demolition in the AEC context. Summarizing the existing guides to circular cities, such as the CE guidance for construction clients by UK Green Building Council [4] and ISO/TC 323 standard by International Organization for Standardization [5], construction circularity could be understood as the goal of designing out wastes and pollution and keeping construction materials in use through strategies including reuse, repair, recover, restore, refurbish, remanufacture and recycling to reduce environmental impact, emissions and improve sustainability. Despite the great potentials of CE strategies, past research focused on investigating the lifecycle assessment (LCA) methods or experts' opinions to partially identify the benefits and drawbacks of the specific CE approach adopted in construction projects. An overview of exactly what and how the different available approaches could contribute to CE remains missing from the existing body of knowledge but requires systematic investigations.

To address this gap, this study adopts a systematic literature review method to find a total scope of key approaches to CE. The remainder of this paper is structured as follows. Section 2 describes the review methodology, followed by the detailed findings of key approaches in Section 3. Section 4 concludes the study together with a discussion of the findings and future work.

2 Methodology

This study adopted the systematic literature review method for the identification of key approaches to CE. As theoretically defined by Wolfswinkel et al. (2013) [6], a systematic literature review method is used to comprehensively search the relevant body of literature in the easily accessible publication databases with comprehensible search rules or search criteria. Therefore, the method is considered suitable in this study for assessing the details of the scientific publications related to the CE. The publication database of the Web of Science Core Collection was scanned for the retrieval of the literature across publication years ranging from 2011 to 2021. The search rules were used to ensure the relevance of the selected literature to the detailed topics of CE (presented in Table 1). To be specific, the dimensions of "How", "Where", and "When" CE could be achieved were investigated in parallel using the connecting logic operator "AND". Within each dimension, the keywords, such as "Reuse" and "Recycle" concerning "How" CE could be achieved, were connected using the logic operator "OR". Using the search rules, the initial search returned 146 journal articles. This number was reduced to 45 by filtering to specific fields in Web of Science. The selected fields were civil engineering, construction building technology, and architecture. Fields such as navy engineering and agricultural engineering were excluded. Next, the first author read the full contents of the 45 articles in-depth and examined whether the contents were aligned with the key approaches to CE. Articles that only provided literature review analysis were excluded. In the end, a total of 40 articles were selected.

From the in-depth review of the 40 articles identified, the authors first derived five categories to which the emerging key approaches would belong. Then the 40 articles were coded to link main research findings with specific key approaches in each category. The coding processes were set up for iterative modifications and enlargements to reduce personal bias as much as possible. Throughout the content review analysis stage, various thematic codes were inductively derived and led to 5 categories: 1) material design, 2) building design, 3) construction and facility management, 4) urban sustainability development, and 5) system precondition. Each category contains a conceptual grouping of the key approaches to CE. For the convenience of coding and easy understanding of the key approaches, each article was exclusively assigned to one category based on its most significant circularity concepts. A description of the key approaches is provided in the following section.

Table 1. Search rules used in Web of Science

How (OR)		Where (OR)		When (OR)
Reuse	**AND**	Building	**AND**	Design
Recycle		Housing		Production
Reduce		Infrastructure		Manufacturing
Refurbish				Installation
Recover				Construction
Restore				Maintenance
Regenerate				Operation
Circular				End-of-life
				Deconstruction
				Demolition

3 Findings

Five categories and fifteen key approaches to realizing CE resulted from the coding process during the systematic review. The probabilistic distributions of the articles by regions, journals, and years are presented in the supplementary file [i]. The list of these approaches is shown in Table 2.

3.1 Material design

In this broad category, the emerging material design solutions for CE include LCA-based design for reuse and design through waste recycling, focusing on investigating CE strategies on a building material or a relatively micro level.

(1) LCA-based design for reuse

Unlike conventional LCA applications that focus on evaluating the environmental impact of building materials from existing use, the LCA-based design for reuse emphasizes the impact when the materials originated from prior buildings will be reused again in future buildings. New equations for the allocations of impacts of a building component over the building use cycles have been recently proposed to account for the material reuse potential, which could be adapted based on the existing LCA guides and norms (e.g., Product Environmental Footprint Category Rules Guidance [7]).

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[i] The supplementary file can be accessed via: https://bit.ly/3o6ZNO2

For example, De Wolf et al. (2020) [1] proposed a distribution allocation method that distributed the impacts of production and end-of-life stages in proportion to the number of life cycles of reused building components and tested it for the loading bearing components of an office building project (Kopfbau Halle 118 in Switzerland). Their LCA calculation results incentivized design with upstream reuse and downstream reuse [1]. Oh et al. (2016) [8] and Saint et al. (2019) [9] conducted similar LCA analyses for the optimal sustainable design of the concrete-filled steel tube columns and the solar water heater, respectively. Their findings indicate that the LCA-based design could reduce the energy payback period, greenhouse gas emissions, and building maintenance and operational costs. These studies manifested the importance and usefulness of new material design methods based on LCA and reuse concepts; however, the primary challenge behind using LCA-based design for reuse is the difficulty of estimating and predicting the number of life cycles that building components can be reused.

Table 2. List of key approaches identified from the reviewed literature

Category	Key approach	Supporting literature
Material design (micro level)	LCA-based design for reuse	[1], [8], [9]
	Design through waste recycling	[10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]
Building design (meso level)	Design with reuse	[22], [23], [24]
	Design for deconstruction	[25], [26], [27]
	Circularity evaluation	[28], [29], [30]
Construction and facility management (project management level)	Lean construction	[31]
	Service life prediction	[32]
	Digital coordination platform	[33], [34], [35]
Urban sustainability development (macro level)	User-centered community design	[36]
	Sustainable requalification	[37], [38]
	Urban circularity mapping via open data	[39], [40]
	Nature-based design	[41], [42]
System precondition (system boundary level)	Product-service business model	[3], [43]
	Closed-loop supply chain network	[44]
	New role definition	[45]

(2) Design through waste recycling

Unlike most dominating design practices that favor using new materials, design through the waste recycling approach focused on discovering the methods and benefits of using recycled materials. An intense claim has been around the quality of construction material wastes following the local building codes, which could lead to the instability of final recycled products to affect the physical and mechanical properties of buildings. However, recent studies have revealed the satisfactory mechanical performance of construction materials recycled from wastes that meet design intents. Examples include recycling wood wastes in cement composite materials for a newly designed wood wool cement board [10], recycling aggregates from crushed ultra-high durability concrete as a substitute for the natural aggregate to deliver high performance concrete under extremely aggressive exposure conditions [11], embedding granulated recycled particulate material additives into 3-D printer materials, concrete and pavement [12], incorporating fine recycled aggregates from demolition waste in rendering mortars [13], developing building bricks using steel industry electric arc furnace dust as admixture into standard clayey raw materials [14], recycling carbon-fibre and glass-fibre reinforced thermoplastic composite laminate waste into high-performance sheet materials [15], recycling the industrial by-product in the stabilised rammed earth materials [16], recycling the limestone, siliceous concrete fines and shatterproof building glass from demolition waste in new blended cements [17], designing exterior cladding using recycled textiles and drinking water treatment wastes [18], recycling rammed earth from heritage building for future building purposes [19], recycling wood and biopolymer for particleboards to replace the conventional panels made of synthetic polymers and virgin wood particles [20], and recycling glass waste in preparation of the gypsum composites for construction [21]. These studies were primarily conducted through rigorous and comparative lab experiments combined with environmental impact analysis, ensuring the proper characterization (e.g., thermal conductivity, surface roughness, loading capacities) of recycled materials for building needs. Besides, these materials have been demonstrated as environmentally benign alternatives to reduce up to 95%

of environmental impacts compared to conventional material design and usage scenarios.

3.2 Building design

In this broad category, the emerging building design solutions for CE include Design with reuse, design for deconstruction, and circularity evaluation, focusing on investigating CE strategies on a building system or a relatively meso level.

(1) Design with reuse

Unlike the conventional design of building systems and structures that focuses on assessing the structural properties of newly manufactured building elements, the design with the reuse approach highlights the reuse of a stock of reclaimed elements to ensure optimal structural geometry and topology. This approach is slightly similar to the LCA-based design for reuse approach, both of which need to rely on accurate estimation of reuse cycles; however, the latter one does not extend to the reuse of the entire modules or assemblies without much reprocessing for future projects [22, 23, 24]. Brütting et al. (2019) [22] innovated a train station roof structure of complex layout by reusing the disassembled electric pylons from a power transmission line in Switzerland, which reduced an up to 63% environmental impact when compared with a same weight-optimized conventional design. With the same idea of such large-scale reuse applications, Chen et al. (2020) [23] and Nijgh et al. (2020) [24] designed brick-lined railway tunnels and a steel-concrete demountable car park building, respectively, which enabled great adaptability of large-scale building systems by reusing the disassembled elements.

(2) Design for deconstruction

Design for deconstruction is a design approach to extend the service life of the different elements of a project (e.g., building components), which is different from the design with reuse approach that usually sources reused elements from other deconstructed or demolished projects. The essential idea behind the design is the consideration of deconstruction, which is a process of reclaiming building materials and elements “as-is” (e.g., windows, doors) [25], but it is always challenging to perform. Eberhardt et al. (2018) [26] have found that the material composition significantly influences the deconstruction performance. Besides, different technological tools have been developed to facilitate the design for deconstruction. For example, Sanchez et al. (2019) [27] proposed a semi-automated selective deconstruction programming approach to optimize the disassembly sequences, which was based on 4D BIM that collected the appropriate level of details of deconstructed building information (e.g., the exact location of nails in wood framing). These semi- or fully- automated technical methods could increase the efficiency of deconstruction planning and design for deconstruction; however, they have not been widely studied, and case studies have been lacking in the existing literature.

(3) Circularity evaluation

Circular evaluation is the approach to ensure the technologies, processes, and materials are appropriate to meet circularity needs. A few circularity evaluation frameworks and taxonomy of circular indicators have been established based on best practices of using general CE concepts; however, they do not comprehensively inform the specific design and technical requirements of buildings. Finch et al. (2021) [28] developed twenty circular performance criteria for the external functional layers of New Zealand light timber platform framing, which covered a wide range of characteristics (e.g., thermal resistance, waterproofing) of recycled and reused materials. Besides, there are individual circularity indicators used for different circularity aspects. For example, the embodied greenhouse gas emissions indicator was investigated to map the circularity performance of four Danish projects [29]. For wastes and demolition, the indicator of waste diversion rate was calculated to assess the effectiveness of waste management in the residential construction sector in Australia [30]. The results from these evaluations helped project owners determine economic benefits from reuse and recycling and helped local government and regulatory bodies benchmark and develop circular construction programs and policies for sustainable urban development.

3.3 Construction and facility management

In this broad category, the emerging construction and facility management solutions for CE include lean construction, service life prediction, and digital coordination platform focusing on investigating CE strategies on a project management level.

(1) Lean construction

Lean construction principles and methods are not new in the construction domain, including pull planning / reverse engineering, takt planning, and the Last Planner® System. However, the interaction between lean construction and CE has not received much attention until recent time. Benachio et al. (2021) [31] suggested incorporating reversible building design processes into the design for deconstruction processes in which a design could consider all life cycles of building elements and guarantee their high reuse potential in future projects. From the selected literature, only one article discussed lean construction to achieve circularity [31]; therefore, the lean construction methods seem to receive much less attention when compared to the other key approaches.

(2) Service life prediction

Service life prediction is an inevitable part of life cycle assessment and is aligned with life cycle costing. The building lifespan has significant effects on the overall environmental performance of a building. For example, the longer the lifespan and more reuse cycles, the less embodied environmental impacts [32]. Therefore, an accurate prediction of the life span of building elements and the number of life cycles is considered essential to allow a reliable planning process for CE. Detailed mathematical prediction models were not seen from the selected articles, but it is likely they were excluded earlier during the literature search. However, many LCA-related case studies in the selected literature referred to norms and standards (e.g., ISO 15686 Part 2 and Part 8 [32]) to predict the service life of building elements.

(3) Digital coordination platform

A digital coordination platform approach is required not only for a Construction 4.0 context but also for a circular construction one, centered around applying BIM technologies to enhance the information exchange and decision-making processes with quick information updates in circular projects. The practical implementation of a digital coordination platform can be carried out using different software solutions and plugin functions. Eray et al. (2019) [33] and Fargnoli et al. (2019) [34] developed BIM-based solutions to connect the 3D information of building elements with the building facility management needs and the adaptive reuse plans, which gave more certainties to stakeholder communication and established clear agreements. Besides, blockchain technology (i.e., a distributed ledger system) has become an emerging topic in circular construction. For example, Kouhizadeh et al. (2019) [35] analyzed multiple case studies of blockchain adoption for circularity purposes. They found that leveraging blockchain with RFID, QR codes, and other sensors could prevent data falsification among stakeholders and increase traceability of reused and recycled materials. They also found that a particular form of blockchain-based contractual system, the Ethereum-based smart contract, could trigger automatic payments and automatically store protocols with material contractors in the construction supply chain. Compared to the other key approaches, the development of BIM-based or blockchain-based digital coordination platforms to realize CE was not seen extensively in the existing literature.

3.4 Urban sustainability development

In this broad category, the emerging urban sustainability development solutions for CE include user-centered community design, sustainable requalification, urban circularity mapping via open data, and nature-based design, focusing on investigating CE strategies on a macro level, e.g., urban, city, and country level.

(1) User-centered community design

A user-centered community design approach is an opportunity to drive design in response to user needs and improve circularity and sustainability. The engagement with inhabitants and users is important from the early project planning phase. Lucchi and Delera (2020) [36] enhanced the historic public social housing community in Milan by involving inhabitants to provide knowledge of the local social-economic conditions for selecting appropriate sustainable retrofit solutions. The findings indicate that participatory actions are also important for empowering the environmentally responsible design for public housing neighborhoods.

(2) Sustainable requalification

A sustainable requalification approach focuses on the requalification of services and physical spaces to improve social aggregation for a new suburb and urban metabolism. Mamì (2014) [37] suggested making communities (in Italy) independent from the view of waste disposal and instead promoting the self-sufficiency principle (e.g., smaller and cheaper transportation service networks and plants work together to enable waste cycle management that transforms wastes into useful resources). Considering the same principle, Serena and Altamura (2018) [38] prepared a harvest map in the area between Como and Milan to identify, within the network of local companies, waste materials that could be used in the recovery of a historical Villa on the Lake Como constructed with load-bearing stone masonry and wooden floors. The requalification of services and physical spaces enhanced the service and space integration for circularity, but the distance between plants and the quality of transportation infrastructure becomes fundamental to affect the environmental and economic outcome of using the approach.

(3) Urban circularity mapping via open data

Urban circularity mapping via open data is an approach that spatially models the building blocks in an urban area and quantifies their environmental requirements or impacts. Following this idea, Marcellus-Zamora et al. (2020) [39] used geo-referenced data on reused construction and demolition wastes in LEED databases to quantify the waste material flow (e.g., how many materials have been recycled or reused) in the city of Philadelphia. Their findings, which showed that 77% of the sampled buildings had materials with recycled contents, have incentivized future data collection for tracking the material recycle and reuse. Using a slightly different quantification approach that is based on BIM and GIS, Stephan and Athanassiadis (2017) [40] developed a high-resolution model to map out the embodied energy intensity of the city of Melbourne considering the typology, geometry, and age of each building in the municipal's open database. However, the urban circularity mapping is quite challenging in many places due to the lack of a local open database and the lack of the computational power to complete the quantification process for all building stocks. Nevertheless, it provides a great opportunity to inform city and urban planners to rebuild cities and communities towards sustainability by looking at the environmental performance of each building.

(4) Nature-based design

At the urban level, the nature-based design approach concerns using nature-based solutions to reorganize the relationship between the built environment and the ecological environment. For example, Mussinelli et al. (2018) [41] advocated the integration of trees, water bodies, and other natural green areas with the urban infrastructure to support urban regeneration. A more specific application of this approach was illustrated in the study of Sierra-Pérez et al. (2018) [42], where they introduced the cork insulation boards as a natural material solution for retrofit building design in the Barcelona metropolitan area to reduce environmental impact and retrofitting cost, considering that cork is a very interesting forest-based material for many industrial sectors as a natural and renewable material. The nature-based design provides a great opportunity for one sector (e.g., the cork oak forest sector) to diversify its market and produce materials that fit into another sector (e.g., the housing sector). This potential synergy is also highly relevant to the sustainable requalification approach as the interaction of sectors and companies should not be neglected.

3.5 System precondition

In this broad category, the emerging solutions for establishing critical system preconditions for construction circularity include product-service business model, closed-loop supply chain network, and new role definition, focusing on investigating CE strategies under particular system boundaries.

(1) Product-service business model

A product-service business model has become an important precondition for smooth implementation of circularity approaches because of the redefined material value proposition (e.g., leasing and sharing), new ways of building, and the change in the ownership of materials. Based on structured interviews, Kanters (2020) [3] found that the product-service business model is required by the circular material providers to offer a service with long-term responsibility. It also means that the building owners and tenants do not need to own building materials if they do not want to own them. For the business model to succeed, the challenge is that the providers have to ensure the services are well-designed to meet clients' needs [43] and preferably have a long lifespan.

(2) Closed-loop supply chain network

A Closed-loop supply chain network is required to support the circular material flows that optimally locates the industrial facilities and plants to manufacture and distribute products and collect and recycle end-of-life products. Using the mixed-integer linear programming (MILP) model, Accorsi et al. (2015) [44] optimized the geographic location of raw material suppliers, manufacturing plants, distribution centers, collection nodes for wastes, landfills, and recycling centers together with the optimization of the allocation of transportation flows. The supply chain network coupled with the transport geography is a fundamental precursor to realizing construction circularity.

(3) New role definition

A new role definition is necessary when defining the supply chain network towards circularity and project stakeholder collaboration processes [45]. As new rules and procedures are adapted for circular strategies, new roles must be established and defined accordingly. Based on the analysis of multiple case studies concerning the coordination of reuse of building materials, van den Berg et al. (2020) [45] found that new roles of "separator" demolish subcontractors were created for demounting, selecting and delivering reused materials for other project sites. How effective the coordination activities and construction circularity should depend on whether the new roles are aligned with the circularity approaches and contractual terms.

4 Conclusions and future work

This study takes a systematic literature review to find an overall scope of key approaches to construction circularity. From the 40 selected publications, five broad categories representing different levels of circularity implementation: 1) material design, 2) building design, 3) construction and facility management, 4) urban sustainability development, and 5) system precondition, were identified. Those categories were further decomposed into 15 key approaches to realizing CE.

The current body of knowledge concerning construction circularity emphasized the new experiments and LCA analysis heavily to validate the potential of recycled and reused materials regarding their environmental performance and mechanical properties. However, this review finds that the other emerging but less studied topics (i.e., reflected in less than two articles), such as the lean construction methods, the digital coordination platform, and the urban circularity mapping via open data approach, etc., are worth considering to realize construction circularity. This review finds that BIM-based and blockchain-based platforms could increase the traceability of reused and recycled materials, which in turn facilitates the communication between project stakeholders concerning what, how, and when the materials should be used within the estimated number of life cycles. At the urban level, industrial symbiosis through nature-based design and sustainable requalification is needed for connecting the demolition sites, recycling plants, and construction project sites to allow efficient use of resources. New business models and new role definitions are also required to support the implementation of circularity in construction.

Besides the identified mainstream key approaches from the selected literature, researchers mentioned the importance of establishing revised legal and contractual frameworks and renewed material certification systems for reusing and recycling materials. For example, the Australian draft standard for recycled structural timber does require further treatment; however, treatments typically have a specified effective lifespan, which could impose a high legal risk for local builders. Besides, local government funds and tax policies lacked discussion in the literature, but they are considered important drivers. However, these legal, risk, financial and contractual topics have not been systematically investigated and require more expert knowledge and future research work.

Although different approaches to construction circularity seem to have their respective potentials, it remains difficult to devise a complete circular construction approach that treats all aspects fairly. Overall, this review shows the necessity to integrate stakeholders, service centers and plants, transportation networks, and local authorities to realize construction circularity at the micro, meso, and macro levels.

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