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Identification of parameters and indicators for implementing circularity in the construction industry

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Abstract

The increase in population, rapid urbanization, the required infrastructure development, the linear development model adopted by the construction stakeholders, and the unaccountability of construction waste have put tremendous stress on existing natural resources. The world has witnessed a situation where resource optimization through mitigation strategies has become significant for sustainable construction. A circular economy keeps the resources in the loop for the longest possible, eliminating waste from the system. This paper attempts to identify the parameters and relevant indicators for bringing circularity to the construction industry. During the research, 144 indicators were identified through a literature review which was followed by a three-round Delphi survey to attain consensus from 30 experts. Finally, after three rounds, 78 indicators were shortlisted, which received maximum consensus among the experts (W = 0.75). Construction stakeholders and decision-makers can use the identified list of indicators to bring circularity to the construction industry.

Keywords: Circular economy, Circular built environment, Circularity indicator, Literature review, Delphi technique

Introduction

The rate of natural resource consumption will be twice the rate of production in 2030, and the rate will increase three times by 2050 with the exponential increase in the global population [1]. Almost 68% of the world's population is estimated toe in cities by 2050 [2]; therefore, the demand for residential infrastructure and services in urban areas is putting an extraordinary burden on existing natural resources [1]. Globally the rate of consumption of resources (almost 50%), energy consumption (40%), greenhouse gas emissions (35%), and generation of residues (approx. 35%) are very intensive in the construction industry [3]. The main cause is that the construction industry primarily adopts the linear development model of 'take, make, consume and dispose' [3–5]. The built environment is under tremendous pressure to mitigate the impact and minimize waste & circular economy approach in the construction industry can help achieve the objective [4]. With the increasing trends toward resource consumption by the construction industry, circular strategies can help in achieving sustainable construction [1]. This paradigm shift will help reduce the burden on natural resources and waste generation [6]. The circular model aims to be a restorative process that eliminates the system's waste and considers the existing commodity as a resource to be kept in the loop for the longest possible [3].

The widely promoted 3R principles of (Reduce, Reuse & Recycle) extend up to 10R principles (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle & Recover) in a Circular Economy [7], which replaces the "End of Life" of buildings towards the recovery of materials and elements [3]. The lifespan of major building typologies (residential, commercial, and public) is estimated to be 50–75 years which has been reduced to 20 years currently [8]. The attitude toward designing buildings for a single life [3] contributed significantly because of societal and market factors to construction & demolition waste globally. This construction & demolition waste could have otherwise been used as a resource, as most of the building elements and layers have different design lives compared to the building [9].

The awareness of the use of circular economy in the construction industry is fair, and the industry's transition is unavoidable. The circular economy concept has gained global academic, government, and organizational recognition. Various initiatives are being taken across the globe toward embracing a circular economy in the construction industry. The different initiatives are the Circular Economy Action Plan, European Green Deal, EU Framework Level(s), Towards a circular economy: A zero waste program for Europe, and Spanish strategy for the circular economy, Waste and Resources Action Program, UK, Zero Energy Standard Brazil, 2017, National Circular Economy Roadmap, Australia, 2020, Circular Economy Promotion Law (2009) & Cleaner Production Promotion Law, China, Law for Promotion of Efficient Utilization of Resources, Japan, 2000, Deconstruction of Building Law, USA, 2019, Environment Protection Act, USA, etc. [10].

Even though the circular economy has gained the attention of researchers, construction stakeholders, policy, and decision-makers in the last decade [3, 4] the idea is still lacking in the development and application of tools, implementation knowledge, and circular business models in the industry [3, 5]. The figures indicate that the current global economy is only about 6% circular. No standardized way or comprehensive methodology exists for evaluating buildings' circularity [11]. This article presents a comprehensive list of parameters and indicators to be considered for bringing circularity to the built environment identified through literature and validated through a Delphi survey by experts.

Methodology

The methodology adopted was a systematic literature review [3, 12] to understand the knowledge development in the field of circular economy in the construction industry and identify the indicators (Tables 1, 2, 3, 4, 5 and 6) that are relevant to bringing circularity into the built environment. A total of 144 indicators were identified from the literature review which contains journal articles from 'Web of science and Scopus' electronic database. The identified 144 indicators from literature reviews were further assessed by an empirical analysis using the Delphi method as a research tool. The Delphi method helps achieve a consensus through questionnaires and expert feedback [13, 14]. The Delphi method helps develop a forecast and understand the issues, opportunities,

Table 1 Parameters and indicators identified for design framework & practices for CE

Parameters	Indicators	References
Design Framework	• Closed loop of the flow of construction Materials/Elements • R principles adoption • CE strategies at all levels • Stakeholder Collaboration • Design Guidelines • Circularity Tool	[3, 7, 16–24]
Practices for Circular Economy	• Design for Disassembly • Adaptability • Standardization • Design for Multiple Use • Flexibility & Resilience • Disassembly Sequence Plan • Demountable Components	[3–7, 17, 18, 25–48]

and solutions and is particularly appropriate for developing indicators [15]. Forty-three experts from academics, industry and government offices were identified in architecture, civil engineering, and environmental planning, out of which 30 experts responded. The experts were both from national and international locations and a snowball sampling method was used to conduct the survey. The consensus was achieved following the 'iteration' and 'revision' of the opinion of experts in three rounds.

Achievement of consensus is essential in the Delphi method [13, 92], and statistics showing less variance are the ones that display greater consensus [93]. The study conducted required fulfillment of three criteria for obtaining the consensus: Interquartile Range (IQR) ≤ 1 [94], the standard deviation (SD) < 1 [95], and Median ≥ 4 [96] on a 5-point Likert Scale. The non-attainment of any of the three criteria results in a lack of consensus [97].

Delphi method comprises a vital component, 'Iteration,' which has a provision of revision of the opinion of experts within the broader perspective of the entire panel by providing feedback between rounds and identifying the attainment of consensus and termination of the iterative process [97]. The study proposes to use Kendall's W (Kendall's coefficient of concordance: non-parametric statistical test) to evaluate the level of agreement among the experts [98] and to judge whether the consensus has increased in subsequent rounds [99]. Strong agreement is indicated by $W \geq 0.7$, $W = 0.5$ indicates moderate agreement, and $W < 0.3$ indicates weak agreement. To test the consistency of the ranking, the study used Spearman's correlation coefficient ρ, wherein $\rho = +1$ indicates a perfect positive consistency and $\rho = -1$ indicates the perfect negative consistency of ranks.

Literature review

A systematic literature review was conducted with the help of a scientific database (Web of Science and Scopus) search related to a list of keywords associated with the circular economy in the construction industry. The research articles were further categorized under six headings based on the identified keywords: Frameworks/Models/Tools for Circular Economy in the Construction Industry (1), Circular Economy and Building Life Cycle Stages (2), Circular Economy and Construction & Demolition Waste Management

Table 2 Parameters and indicators identified for bringing CE in building life cycle stages

Parameters	Indicators	References
Predesign/ Design Stage	• Modular/Prefabricated Buildings • Adaptive Reuse • Building Material/Components Stock at their end of life • CE inclusion in Tenders • Use of BIM Tools • Environmental Product Declaration • Design out Waste • Simple Open Planning • Designing in Layers • CE Consultant • Green Design Methods • Design for Ease of Maintenance & Repair	[3–5, 7, 16–18, 21, 23–33, 37, 41–44, 46, 49–56]
Manufacturing Stage	• Durability/Longevity • Design for Remanufacture • Circular Supply Chain • GHG Emissions • Efficient use of water resources • Use of Renewable Energy Sources • Circular Labels by Professional Bodies • Reversible Connections • Repeated Structural Grid with regular dimensions • Developed Transport Systems • Matching of Supply and Demand of Reused/Recycled Materials • Dematerialization • Innovative Production Process • Design Networks • Green building Procurement • Less use of Packaging	[3–6, 11, 17–19, 26, 27, 29–33, 39, 40, 44, 48–50, 57–62]
Construction Stage	• Reuse of materials in new construction • Building Construction Methods • Smart Construction Technique • Circular Procurement of Materials & Components • Use of skilled local workforce • Fixing and Material Technology as per CE • Use of Nuts and Bolts • Mobile Partition Walls • Use of isolated or Pile Foundation • Green Construction work • Increase in performance of building materials • Offsite construction • Lean Construction • Optimization of Components • Safe storage of construction materials at site	[3, 5, 6, 11, 17, 19, 20, 25, 26, 28, 31, 32, 39, 40, 44, 46, 47, 49–51, 60, 63–69]
Operation/Use Stage	• State of building materials during use and EoL • Use and modalities for operation in line with CE principles • Energy Consumption • Preventive Maintenance • Healthy and Comfortable Spaces	[3, 6, 17, 26, 31, 49, 70]

Table 2 (continued)

Parameters	Indicators	References
End of Life (EoL) Stage	• Design for Demolition • Selective Deconstruction • Reuse Potential • Recycling Potential • Adaptive Reuse Potential • Building Restoration • Pre demolition Audit • Demolition Plan • Inventory of Building materials and elements for reuse • Presence of a Local Recycling Centre • Deconstruction Labor Speed • Technologies for enhancing the quality of salvaged materials • Recycling Network • Advanced Recycling Technologies • On-site Waste Management • Recycling Rates & Targets • Circularity Score • Time for Disassembly • Recycled Product Demand	[3, 5, 6, 10, 16, 17, 19, 20, 23–27, 31, 32, 35, 38, 40, 41, 44, 45, 48, 49, 52, 56, 61, 63, 66, 67, 69, 71–80]

Table 3 Parameters and indicators identified for fostering CE through C&DWM

Parameters	Indicators	References
Waste Reduction	• Prediction of waste to be generated at early design phases • Design for reuse & recovery • Design for Recycling • Design for Waste Efficient Procurement • Zero waste Site • Fit Out Waste Management	[5, 17, 18, 23, 24, 26, 28, 36, 44, 46, 47, 69, 72]
Construction & Demolition Waste Management (C&DWM)	• Warehouse for Demolished construction materials/elements • Local-level waste management company for handling and supplying • Urban Mining & Recycling Unit • C&DWM Tools • Distance of C&DW Recycling Plants • Quality of C&DW • Standards and Specifications towards the use of CDW • Training & Surveillance Practices related to C&DWM • Use of mobile phone applications for valorizing, reuse & recycling of C&DW • Defining a System Boundary & Assessment Period for C&DW	[19, 20, 41, 48, 61, 78, 81]

(3), Building Materials/Elements fostering circularity in the construction industry (4) Local Governance and Institutional Framework (5), and others (6).

Practices/frameworks/models/tools for circular economy in the construction industry

As per the scientific literature, the theoretical knowledge development of circular economy in the construction industry is good [3, 25], but the knowledge development of the implementation and practical use of circular economy for effective design and construction is still low [26–29], because of the complex supply chain and short-term goals of companies in the construction industry [3]. In the construction industry, the role of

Table 4 Parameters and indicators identified for bringing CE through building materials

Parameters	Indicators	Citations
Selection of Material	• Use of recycled materials • Use of low-carbon materials • Use of natural/bio-based materials • Use of secondary building materials • Durable Materials • Use of locally available materials • Use of waste from other industries as raw material	[3, 11, 31, 32, 39, 44, 50, 60, 66, 67]
Flow of Material/Components	• Information on the materials used from the early stages • Presence of Material Passport & MP Consultant • Circular Material Library • Supply & demand of salvaged building materials • Supply & demand of secondary building materials • Self Sufficient Region	[3, 5, 11, 17, 19, 20, 31, 39, 40, 44, 50, 52, 54, 59–61, 66, 67, 69, 70, 79]
Green Building Standards & Certification System	• Building Certification System • Certification System of reused/recycled materials/components	[18, 19, 32, 61]

Table 5 Parameters and indicators for bringing CE through governance capacity & institutional & regulatory framework

Parameters	Indicators	References
Governance Capacity	• Subsidies and Tax relaxation for CE strategies • Financial Incentives • Carbon taxes and Landfill bans • Demolition taxes, tax raise on use of virgin materials • Landfill Tipping fees & disposal tax • Increased taxes on the use of foreign prefabricated components • Funds and incentives for Retrofit of existing constructions • Availability of demolition fund	[5, 10, 17, 19, 20, 32, 40, 50, 61, 73, 77, 78, 82]
Institutional & Regulatory Frameworks	• Flexibility in existing building codes and regulations • Incorporation of CE in building codes • Carbon taxes and Landfill bans • Effective C&DWM Regulations • National & Regional level CE Action Plans • Policies related to C&DW disposal in public landfills	[17, 31, 50, 68, 78, 81, 83–85]

architects and designers is significant [30] and there is a need for a holistic, systematic approach and a collaborative network among construction stakeholders at all levels to apply circular economy principles in buildings [26, 30, 71].

Frameworks for circular economy in the construction industry

A range of frameworks and methods have been developed to support the circular economy in the construction industry. A design framework for narrowing (refuse, rethink, reduce), slowing (reuse, repair, refurbish, remanufacture, repurpose), and

Table 6 Parameters and indicators for CE in CI through other factors: socio-cultural, financial & environmental performance

Parameters	Indicators	References
Socio-Cultural	• Skilled and Informed Workers and Sub-contractors • Knowledgeable Designer (Architect & Engineers) • Public awareness and Willingness to Change • Educated Client & Willingness of the Client to spend more on circular buildings • Integration of CE in university curriculum at all levels • Designer's understanding of social behavior of people • Provision of CE training and knowledge exchange programs • Sharing of resources • Shift from short-term thinking to long-term thinking • End User Perception • Social Integration of new buildings	[5, 17, 18, 20, 21, 25, 30, 31, 41, 47, 50, 52, 61, 63, 78, 81, 82, 86–88]
Financial	• Presence of a Circular Business Model • Life Cycle Costing • Material Recuperation Cost • Availability & Presence of Circular Value Chain • Low-cost materials & technologies • Deconstruction Labor Cost • Cost-Effective Recycling Solution	[5, 6, 17, 19, 27, 38, 48, 66–68, 78, 79, 82]
Environmental Performance	• Life Cycle Assessment • Material flow analysis	[27, 48, 49, 56, 59, 64, 89–91]

closing the resource loop (recycle, recover) helps devise strategies for circular business models [49, 63, 100]. The Ellen McArthur Foundation ReSOLVE framework: Regenerate, share, optimize, loop, virtualize and exchange for the optimization of resources supports a circular economy [101]. Valeria developed a systemic framework categorizing circular economy interventions into four groups: 'RISE'- Research & Realize, Implement, Enable & Support, each considering 10R principles. The research focused on interventions in the construction & demolition sector through identified indicator sets toward circularity. The framework/tool for the design of components of buildings [100] and buildings as a whole [16] has been developed, which supports a circular built environment. Pomponi and Moncaster [29] developed a three-tiered research framework (macro-cities/neighborhoods, meso- building level & micro- building components, and materials) from a CE perspective and identified six fundamental dimensions encouraging interdisciplinary CE research in the built environment). Antwi-Afari et al. [57] developed a research framework consisting of eight different themes and further proposed a framework for circular economy implementation and evaluation effectively based on gaps in the circularity concept in the construction industry. Charef and Lu [18] developed an entity-relationship diagram of the identified uses of BIM for implementing a circular economy in the construction industry. The R principles [7, 102] and frameworks towards circularity mainly focus on the micro level components and materials [30, 31] and macro level- city level [31], and the meso-building levels information are limited, hence universal guidelines and frameworks and common language for designers are required which can help in considering CE at all levels [30]. There is a need for an interdisciplinary research approach for developing tools and methods for circular practices in the construction industry [30]. Malabi Eberhardt et al. [63] developed nine environmental design guidelines for circular building components through life cycle assessment and material flow analysis application.

Practices for circular economy in construction industry

Design for disassembly & adaptability is the circular strategy highlighted by most of the researchers in the literature review [3, 5, 31, 32]. Design for Disassembly and Adaptability has been included in ISO 20887:2020- Sustainability in Buildings and Civil Engineering Works. Anastasiades et al. [4] studied the concept of 'Standardization' and ISO 20887-guidelines for design for disassembly and adaptability, advocating the use of standard size components and their connections in buildings which drives circular construction and, also identified associated problems such as the perception of the designers towards the reuse of components, reluctance of manufacturers to change, and the contractor's perception of standardization as a threat towards design freedom. Different researchers have developed building adaptability frameworks [103, 104], The Learning Buildings Framework [105] and the Adaptable Buildings Design Framework [106] focusing on the physical layers of buildings and help predict the changes in a building's design life. The design strategy for disassembly and the availability of an efficient disassembly sequence plan helps maximize resource recovery [3, 32, 33]. With the design concept for disassembly, the building components and materials can be directly reused in new constructions [4]. The design of a building must be for multiple future scenarios [25, 30, 107]. The use of simple open planning [25, 34], demountable & reusable wall assemblies [17, 27], repeated structural grid with regular dimensions [58], and mobile partitions [25, 34] are conducive for circular construction. The concept of adaptability makes a building resilient to adjust to future needs without getting demolished [4]. The concept of adaptive reuse is significant in reducing construction & demolition waste, and in terms of sustainability, it is considered superior to new construction as it improves the economic, environmental, and social performance of buildings [33, 35, 50, 64]. In the adaptive reuse process, the sequence of disassembly of components and disassembly methods are significant [33]. Modular constructions [36, 37], prefabricated offsite constructions, and standardized elements [4, 108] help in circular reuse of buildings and its components. The strategies of prefabrication and modular construction [36, 37, 109, 110] help reduce the project schedules, reduce waste at the site, reduce the project cost, and improve efficiency, productivity, and safety [32, 111]. The factor of social relationships [38] is significant, and most of the available literature has ignored the social impact, an important aspect that needs to be addressed for the comprehensive integration of a circular economy in the construction industry [49]. Charef and Lu [18] identified 64 factors and their dynamics towards adopting a circular economy in the construction industry. Malabi Eberhardt et al. [63] identified sixteen design and construction strategies for a circular built environment through a systematic literature review and highlighted the missing link between research and practice, which hinders the adoption of the circular economy.

Although there have been a few design support tools developed in the academic literature for the circular economy, the need for the practical use of the same is only partially addressed by the available tools; hence there is a mismatch that calls for a more practice-oriented design support tools development [16]. Dokter et al. [30] explored the perception of designers towards the circular economy in practice and identified a need for change in systems thinking (multiple lifecycles, materials knowledge, alternative economy, & business models) to achieve the circular economy objective.

Circular economy and building life cycle stages

The circular economy practices in the construction industry still focus on only one life cycle stage at a time [3] rather than a holistic approach toward all the stages, from predesign to end of life [7]. During the early design stages, circular economy practices will help maximize waste reduction and resource optimization [23, 64, 112]. The systemic integration of circular economy approaches towards designing and constructing whole life cycle stages of the buildings brings added social, financial, and environmental value [38]. The application of circular economy principles at different life cycle stages has been studied by many researchers [6, 7, 26, 32]. Dams et al. [32] developed a Circular Construction Evaluation Framework, which helps assess the buildings' circularity potential in the early design and planning stages. The academia and practice have a consensus on the importance of early design stages for bringing circularity in the construction industry [30, 113] as almost 80% of the environmental impact is determined during the design stage [114] and almost 70% of them can be minimized and prevented at this Stage [43]. The Circularity principles need to be incorporated right from the early design stages to enhance the reuse, and recovery potential [32] as the project's design phase mainly influences the construction & demolition waste generation [17]. During the early design stage, the better management of construction and demolition waste using BIM tools can help minimize waste and understand the reuse/recovery potential of a building [5, 18, 23, 115]. Charef and Emmitt [21] conducted a literature survey followed by expert interviews to identify 28 uses of BIM towards resource recovery and end-of-life management, overcoming barriers to the adoption of circularity. The introduction of the concept of 'Design for disassembly' at the early design stages increases the adaptability and flexibility of the building and helps in recycling, reusing, or remanufacturing its components [3, 26, 32]. The integration of stakeholders between the design and construction phases helps in reducing construction & demolition waste [17].

The carbon emissions during the manufacturing of building materials in the construction industry are higher than in any other sector [51, 116]. During the manufacturing stage, the Building Material Passport helps estimate the stock of valuable components in buildings at their End of Life [3]. Standardizing building components and parts is an essential strategy during the manufacturing stage to minimize waste [3, 26, 39]. As the construction stage accounts for a large amount of waste [83], the methods of construction are crucial for bringing Circularity [44], modular and prefabricated buildings [36, 37, 39]; the use of smart design, construction, and circular value chain concept can help in achieving circular economy objectives [20, 26] at this Stage. The use of Nuts and bolts to replace glues, nails, and welding will help increase the reusability and recovery of building components [39, 65]. The attention towards adopting circular economy principles during the operation stage of buildings is low [26]. For reusing and repurposing the building material and components, it is essential to maintain them at their best stage and thus improve their durability and longevity [112]. Most of the available literature has not considered the concept of waste management during the construction and renovation stages [49]. The use of circular practices of 'closed loop system and reuse' in fit-out projects can help upcycling and improve recycling rates of the waste generated [72].

The adoption of circular economy strategies at the End-of-Life stage of building has gained the maximum attention of researchers [23, 26, 52]. A large percentage of construction and demolition waste from the buildings is of low quality as the End-of-Life scenario is not considered during the early stages [51]. As there is a lack of awareness of circular economy principles among construction stakeholders [20, 39], most of the construction waste is downcycled [51], which results in low resource recovery [23]. The strategy of 'Selective demolition' [17, 26, 44], 'Sequential disassembly Planning & Methods' [33], 'Adaptive Reuse' [33, 35, 51], and 'Sustainable Renovation' [73] at the end of the life of a building will help in maximum resource recovery and reuse. The durability and recyclable quality of materials [17, 49] are essential factors for incorporating design for disassembly and reuse & recovery at their End of Life. The presence of a database for registering the materials and elements at the end of the life of buildings that can be reused in other construction projects is necessary for circular construction [74]. The presence of a material passport at the end-of-life of buildings helps in identifying the recycling and reuse potential & environmental impacts of materials embedded in the buildings [59]. A few models: BIM-based [22, 23], Deep Learning Model [117], Hybrid Model [118], etc. have been developed in academia to predict the amount of construction & demolition waste at the end of life of buildings which helps in their sustainable management [84]. The design and end-of-life stages are closely related to each other to bring circularity to buildings [17]. Akanbi et al. [75] developed a 'disassembly and deconstruction analytics system' by implementing BIM software to evaluate the end-of-life performance of the design of buildings and hence incorporate the changes required.

Circular economy & construction & demolition waste management

Construction & demolition waste (C&DWM) generation and management is a global environmental problem [89] and creates a risk of resource scarcity [119]. The aim of the circular economy is economic prosperity and improved environmental quality [18], and many studies have identified the economic and environmental benefits of disassembly plans [33] and recycling of C&DW [61, 64]. Still, there is a lack of studies on the benefits or consequences of construction and demolition waste reduction [89], which comes at an upper hierarchy of circular economy principles [102]. This is mainly because of the lack of quantitative environmental assessment methods that help prevent C&DW [89]. A few factors influence construction and demolition waste management (C&DWM) practices, such as population, urbanization, the standard of living, gross domestic product, and regulatory measures [10]. Almost 50% of the total waste is generated during the demolition stage as compared to the other stages of buildings [59] & almost 35% of C&DW is landfilled globally [81]. As per the Waste Framework Directive 2008, Europe the target was to achieve 70% recycling of C&DW by 2020, and circular economy integration for waste recovery and management was significant in achieving this objective [77]. Despite the worldwide attention towards the circular economy in the construction industry, the recovery rate of C&DW is just 20–30% of total construction & demolition waste generated across the globe [120]. This can be attributed to the fact that there are behavioral, technical & legal barriers to effective C&DWM as identified by the research community [68, 84]. To improve the C&DWM practices, it is important to integrate the principles of reduction, reuse, and recycling according to the characteristics of the waste and as per the waste management hierarchy, with avoiding generation given the highest priority and disposal the last priority [81]. The use of information about the amount of waste to be generated right from the early design stages is important in devising strategies for waste prevention conducive to a circular economy [24]. Several models like the BIM-based construction waste prediction model [24], Deep learning-based demolition waste prediction model [117], National waste generation rates-based model [121, 122] has been developed in the academia literature. Liu et al. [47] explored the factors for reducing construction waste onsite using Structural Equation Modeling and identified the awareness level of construction stakeholders, efficient transportation facilities protecting construction materials, material storage at the site, and efficient construction operation at the site as the most contributing factors towards construction waste reduction. Effective C&DWM practices have environmental, economic, and social benefits and involve dedicated participation by all the construction stakeholders, integration at all the life cycle stages of building, and use of effective C&DWM tools and approaches like BIM, RFID, GIS, GPS, Big Data, lean construction, circular economy, zero waste approach, green rating system, waste management plans & technologies [81]. López Ruiz et al. [44] explored the factors towards integrating circular economy principles in the construction & demolition waste management practices and developed a theoretical framework including 14 strategies within the life cycle stages of construction and demolition activities. Esa et al. [40] developed a theoretical framework including three layers (micro-planning & designing, meso-procurement & macro-construction & demolition) for construction & demolition waste minimization at all stages of construction incorporating circular economy principles in Malaysia.

Building materials/elements fostering circularity in the construction industry

The construction industry's consumption of building materials is intensive, and the material demand is highlighted as a problem that needs action for prevention through circular strategies [4]. In a circular economy, building function as material banks [3, 18, 31, 39], and information about the status, quantity, and quality of materials is required (Hossain). The use of BIM in the early design stages can help in identifying the material flow in different stages of buildings [23]. The information about the amount of the material stock & flow of the buildings at the city and regional level and the development of standard practices for reuse can facilitate secondary materials supply for future demand and helps in responsible resource consumption [3, 25, 54, 71]. A circular material library within a region of recycled products based on industrial symbiosis is significant in minimizing resource consumption [70]. The choice of material selection should focus on the use of circular economy principles by recycling or reusing [26], and the practices need to be incorporated at all levels (micro, meso & macro) of construction [3]. The material selected must be of sustainable origin, such as bio-based materials [123–126], secondary raw materials [127–130] and should be durable and of high quality [49, 70]. In the context of circular construction, mostly the research is available in the field of recycling building materials [27, 64, 131], but reuse is preferred over recycling because of the environmental and economic benefits [42, 44, 131]. Arora et al. [54] estimated the stock and flow of materials and components in residential buildings in Singapore and concluded that with the information on building components made of composite materials, the upcycling and reuse potential will be enhanced, which will ensure component-level circularity. Although the method of building component reuse involves the incorporation of design strategies of flexibility and other circular strategies, their reuse as a component rather than separation into building materials has many benefits [54]. The certification of recycled and reused materials [19, 21, 61] and the use of the same at different stages should be prioritized, and construction and demolition waste must be used in new construction activities [36]. Materials recycling is the most common practice in the construction industry, which comes in the lower hierarchy of CE principles [3, 64, 132]. The recycling process often results in downcycling [4] or degrading of the new product derived from the construction & demolition waste which requires a shift in the demolition process to upgrade them and maintain their durability & quality [19]. Detailed knowledge of the materials used is a prefix to improve the recycling rate of construction materials, and early design stages play a significant role in enhancing the recycling rate [52]. The onsite recycling of construction & demolition waste to manufacture surplus secondary raw materials for new construction and existing building renovation helps create a closed-loop system for a circular built environment [79]. Orsini et al. 2019 explored the approaches toward producing low-carbon materials, which reduce the amount of GHG emissions in the production process of construction materials. Bio-based materials such as engineered bamboo products [133] are a sustainable alternative to traditional materials such as concrete and steel, which significantly impact the environment as they offer a renewable supply chain and reduce carbon emissions [134, 135]. Although bio-based materials are a sustainable alternative to traditional materials, they are not yet established as mainstream construction materials [32]. The use of wastes from the construction industry [66, 136, 137] and other industries (agricultural, steel, wastewater treatment, leather, plastic, and petroleum) as construction materials is explored by a few researchers [129, 138] that helps in waste reduction and promotes circular economy.

Governance system and institutional & regulatory framework

Institutional frameworks and local governance systems are essential, and they can act as agents of change in fostering a circular economy in the construction industry [10, 19, 78]. The government can provide funds and incentives to companies that use circular economy strategies in the construction industry [10, 18, 71]. They act as a facilitator, which enables collaboration between varied construction stakeholders, knowledge institutions, and people [19, 139]. The involvement of construction stakeholders right from the early design stages [18, 61] and the collaboration along the construction supply chain [38] across the entire building's life is essential in bringing circularity to the built environment [112]. The collaboration and multi-stakeholder engagement will help devise policies and codes for adopting a circular built environment [17]. The different modes of governance, like self-governance, governance by the provision, governance by authority, and governance through enabling, are studied, and demonstrated by [139] and [19] to explore how cities with multiple modes of governance can help in achieving a circular economy. The local government or municipalities are responsible for waste management in many countries and have recycling targets. With the increasing urban population, there is tremendous pressure on the local government in terms of managing and recycling construction & demolition waste [19]. Condotta et al. 2021 identified the legal and regulatory obstacles to the reuse of architectural, construction & demolition waste and suggested improvement in the regulatory framework for architectural reuse practices. Oliveira et al. [78] developed construction and demolition waste management strategies at the regional level involving the construction stakeholders in Manaus, Brazil.

The literature review also identifies parameters such as socio-cultural, financial, and environmental performance and their respective indicators for bringing circularity in the built environment, as listed in Table 6.

Empirical analysis for indicator selection

A total of 144 indicators under 18 broad parameters were identified from the systematic literature review for bringing circularity to the construction industry. The identified parameters were: (i) Design Framework (ii) CE Practices (iii) Predesign Stage (iv) Design Stage (v) Manufacturing Stage (vi) Construction Stage (vii) Operation/Use Stage (viii) End of Life Stage (ix) Waste Reduction (x) Waste Management (xi) Selection of Material (xii) Flow of Materials/Components (xiii) Green Building Standards & Certification System (xiv) Governance Capacity (xv) Institutional & Regulatory Framework (xvi) Socio-Cultural (xvii) Financial & (xviii) Environmental Performance.

The expert's responses to the identified indicators were analyzed on a 5-point Likert scale, which was carried out in three rounds of an online survey. In the first round, the 144 identified indicators were ranked on a 5-point Likert scale by 30 experts in architecture, civil engineering, and environmental planning. Indicators failing in any of the 03 criteria for attainment of consensus (i.e., $\text{IQR} \leq 1$, $\text{SD} < 1$, and $\text{Median} \geq 4$) were omitted from further consideration. Sixty-six indicators failed in one or more of the given criteria displaying a lack of consensus among experts; hence, they were omitted from the second round of the survey questionnaire. A moderate consensus was observed in the second round of the survey for the 78 indicators with Kendall's Coefficient $W = 0.561$ (Chi-Square = 4115.812 and Degree of freedom = 77). The third round of consultation with experts was conducted, and it was observed that Kendall's Coefficient W increased significantly from 0.561 to 0.752 (Chi-Square = 3071.206 and Degree of freedom = 77), which displayed strong consensus among the participants (Table 7).

The Spearman's Correlation Coefficient $\rho = 0.875$ indicated a strong consistency of ranks by the participants in round 2 and round 3.

Discussion and conclusions

This article conducted a systematic literature review to identify the parameters and indicators for bringing circularity to the construction industry. The reviewed studies were organized based on specific themes/aspects necessary for the circular economy in the

Table 7 Rating results for Delphi and Kendall's coefficient of concordance in round 03 survey

Aspect	Parameter	Indicator Number	Indicator	Median	Standard Deviation	Interquartile Range	Sum of Rank	Rank
Frameworks/Practices/Models/Tools	**Design Framework**	A1	Closed loop of the flow of construction material/elements	4	0.5	1	146	1
		A2	R principles Adoption	5	0.25	0	232	3
		A3	CE strategies at all levels	4	0.73	1	260	4
		A4	Stakeholder Collaboration	4	0.67	1	428	13
		A5	Design Guidelines	4	0.61	1	194	2
	CE Practices	B1	Design for Disassembly	5	0.5	1	307	5
		B2	Adaptability	4	0.48	1	313	6
		B3	Design for Multiple Use	4	0.51	0	334	7
		B4	Flexibility & Resilience	4	0.51	1	357	9
		B5	Demountable Components	4	0.38	0	739	21
Building Life Cycle Stages	**Predesign/Design Stage**	C1	Modular/Prefabricated Buildings	4	0.61	1	426	12
		C2	Adaptive Reuse	4	0.41	0	431	14
		C3	Design Out Waste	4	0.48	0	425	11
		C4	Designing in Layers	4	0.53	0	348	8
		C5	CE Consultant	4	0.38	0	1710	61
		C6	Green Design Methods	4	0.51	1	789	22

Table 7 (continued)

Aspect	Parameter	Indicator Number	Indicator	Median	Standard Deviation	Interquartile Range	Sum of Rank	Rank
	Manufacturing Stage	D1	Durability/Longevity	4	0.49	0	610	18
		D2	Circular Supply Chain	4	0.73	1	598	17
		D3	Use of Renewable Energy Sources	4	0.47	1	553	15
		D4	Circular Labels by Professional bodies	4	0.4	0	1449	51
		D5	Developed Transport Systems	4	0.56	1	1479	52
		D6	Matching of Supply & Demand of Reused/Recycled Components	4	0.67	1	1502	54
	Construction Stage	E1	Reuse of materials in new construction	5	0.49	1	576	16
		E2	Building Construction Methods	4	0.57	1	871	25
		E3	Circular Procurement of materials	4	0.53	0	656	20
		E4	Use of skilled local workforce	4	0.5	1	1691	60
		E5	Fixing and Material Technology as per CE	4	0.48	1	1648	59
		E6	Increase in performance of building materials	4	0.63	1	644	19
		E7	Safe storage of construction materials at site	4	0.51	1	1390	49

Table 7 (continued)

Aspect	Parameter	Indicator Number	Indicator	Median	Standard Deviation	Interquartile Range	Sum of Rank	Rank
	Operation/Use Stage	F1	State of building materials during use and EoL	4	0.51	1	1835	64
		F2	Use and Modalities for Operation in line with CE	4	0.48	1	1899	67
	End of Life	G1	Design for Demolition	4	0.48	1	1076	35
		G2	Selective Deconstruction	4	0.4	0	1075	34
		G3	Reuse Potential	4	0.5	1	1029	31
		G4	Recycling Potential	4	0.45	0.75	1050	32
		G5	Adaptive Reuse Potential	4	0.51	1	1074	33
		G6	Building Restoration	4	0.51	1	1096	36
		G7	Advanced Recycling Technologies	4	0.51	1	1152	37
		G8	Recycling Rate & Targets	4	0.51	1	1481	53
		G9	Circularity Score	4	0.48	1	1378	48
		G10	Recycled Product Demand	4	0.35	0	1363	47
Construction & Demolition Waste Management	**Waste Reduction**	H1	Prediction of waste to be generated at early design phases	4	0.51	1	1220	41
		H2	Design for reuse and recovery	4	0.48	1	1182	38

Table 7 (continued)

Aspect	Parameter	Indicator Number	Indicator	Median	Standard Deviation	Interquartile Range	Sum of Rank	Rank
	Waste Management	I1	Local level waste management company	4	0.48	1	1204	40
		I2	C&DWM Tools	4	0.5	1	1313	44
		I3	Quality of C&DW	4	0.5	1	1396	50
		I4	Standards & Specifications towards use of CDW	4	0.5	1	1199	39
		I5	Training & Surveillance practices related to C&DWM	4	0.51	1	1540	55
Building Materials/ Elements	**Selection of Material**	J1	Use of recycled materials	4	0	0	918	28
		J2	Use of natural/bio-based materials	4	0.51	1	850	24
		J3	Use of secondary building materials	4	0.47	1	911	27
		J4	Use of locally available materials	4	0.51	1	838	23
		J5	Use of waste from other industries as raw materials	4	0.61	1	985	30
	Flow of Materials/ Components	K1	Circular Material Library	4	0.45	0.75	910	26
		K2	Supply & demand of salvaged building materials/components	4	0.5	1	1720	63
		K3	Supply & demand of secondary building materials/components	4	0.57	1	1718	62

Table 7 (continued)

Aspect	Parameter	Indicator Number	Indicator	Median	Standard Deviation	Interquartile Range	Sum of Rank	Rank
	Green Building Standards/Certification System	L1	Building Certification System	4	0.35	0	1618	58
		L2	Certification System of Reused/Recycled Materials/components	4	0.57	1	1600	57
Governance System and Institutional & Regulatory Framework	**Governance Capacity**	M1	Subsidies and Tax relaxation for CE strategies	4	0.47	1	1970	71
		M2	Financial Incentives	5	0.63	1	1954	69
		M3	Demolition taxes, tax raise on use of virgin materials	4	0.57	1	1963	70
	Institutional & Regulatory Framework	N1	Flexibility in existing building codes and regulations	4	0.49	1	1848	65
		N2	Incorporation of CE in building codes	5	0.48	1	1880	66
		N3	Effective C&DWM Regulations	5	0	0	365	10
		N4	National & Regional level CE Action Plans	4	0.53	0	2085	72

Table 7 (continued)

Aspect	Parameter	Indicator Number	Indicator	Median	Standard Deviation	Interquartile Range	Sum of Rank	Rank
Others	**Socio-Cultural**	O1	Skilled and Informed Workers and Subcontractors	4	0.48	0	1929	68
		O2	Knowledgeable Designer	4	0.49	1	2177	77
		O3	Public Awareness and Willingness to Change	5	0.43	0	2112	73
		O4	Educated Client and willingness of the Client to spend more for CBD	4	0.53	1	2122	74
		O5	Integration of CE in university curriculum at all levels	4	0.51	1	2239	78
		O6	Provision of CE training and knowledge exchange programs	4	0.38	0	2159	76
		O7	End User Perception	4	0.5	1	2127	75
	Financial	P1	Presence of a Circular Business Model	5	0.49	1	1347	45
		P2	Life Cycle Costing	4	0.48	1	1547	56
		P3	Low-cost Materials and Technologies	4	0.48	0	959	29
		P4	Cost Effective Recycling Solution	4	0.47	1	1249	42
	Environmental Performance	Q1	Life Cycle Assessment	4	0.48	0	1305	43
		Q2	Material Flow Analysis	4	0.5	1	1357	46

construction industry. The scope of the study is primarily limited to circular economy interventions in the construction and built environments. The article highlights six aspects: practices/frameworks/models/tools, building life cycle stages, construction and demolition waste management, building materials/elements, governance system, institutional and regulatory framework, 18 parameters under each aspect, and a total of seventy-eight respective indicators as listed in Table 7. The identified parameters and indicators are followed by an empirical analysis validated by experts in the field.

The parameters and indicators related to the first aspect of practices/frameworks/models and tools (see Table 1) provide a comprehensive understanding of the current state-of-the-art practices for bringing circularity to the construction industry. The indicators of design frameworks and practices, such as design for disassembly, R principles, standardization, modular construction, etc., have been widely promoted and validated in academic literature and practice. However, a significant indicator, the Circular Business Model, is highly recommended by many researchers, and further work is required in this direction to bring circularity to the construction industry. Using tools such as BIM, circularity tools, deep machine learning tools, and LCA helps in circular construction right from the inception of any project.

The parameters and indicators related to the second aspect of building life cycle stages (see Table 2) are comprehensive and help bring circularity in the construction industry from the predesign stage of a project. Most of the literature focuses on the end-of-life stage of a building, and the approach is mostly recycling, which falls in the lower hierarchy of the identified R principles. And with the integration of a circular economy right from the inception stage, 70–80% of the impact can be mitigated. Therefore, comprehensive integration of circularity during all life cycle stages of a building is suggested for better results. Indicators such as "Energy Consumption", "Greenhouse gas emissions", and "Efficient use of water resources" were identified under different lifecycle stages of a building from the systematic literature review in Round 1 of the Delphi analysis; however, they were further eliminated depending upon the rank provided by the experts. The indicators of energy consumption and greenhouse gas emissions are significant, and the construction industry is one of the prime contributors. Therefore, this article proposes further research in this direction.

The third aspect of circular economy and C&D waste (see Table 3) is significant, as most countries in Europe and Asia have policies and guidelines for managing C&D waste, which brings circularity to the construction industry. Indicators such as "the transportation of construction materials, packaging and storage facilities, and fitting out waste" during construction contribute to the construction waste generated on the site and are mainly ignored in practice. It is essential and required to achieve a zero-waste circular economy concept.

The fourth aspect of building materials/elements and the identified parameters and indicators (see Table 4) is an integral part of the construction industry, and managing this stock can help achieve far-reaching results. The concept of "Urban mining: recovering and reusing waste materials" brings circularity to the construction industry. As buildings are material banks, the number of building materials/elements in the existing stock with the circular economy strategy can help achieve future demand and thus contribute to responsible production and consumption.

The fifth aspect of the local governance and institutional frameworks highlights the parameters and indicators (see Table 5). The knowledge development related to the circular economy in the construction industry is perpetual, but still, the implementation is low. Specific barriers to finance and regulation guidelines impede the acceptance among construction stakeholders. Therefore, indicators such as "funds from the government, financial incentives, regulations, and implementation guidelines" are essential for creating a circular economy in the construction industry. The flexibility in existing codes and regulations as per the region and specific action plans and policies can be vital circular strategies in the construction industry. The parameters and indicators of socio-cultural, financial, and environmental performance (see Table 6) are critical in circular economy practices in the construction industry as the construction stakeholders still resist the change because of a lack of confidence and other market factors. The attitude of the stakeholders, the end-user perception, and the willingness to change are significant in bringing the transition. Although the article identified socio-cultural factors essential for adopting a circular economy in the construction industry, the social dimension is largely ignored in the reviewed papers, and further research can be conducted in this field.

The final list of identified parameters and indicators mentioned in Table 7 not only helps in measuring the level of circular economy transitions in the construction industry and its effect on the environment and economy but also in comparing and evaluating the aspects of circularity in different construction projects. It will help make informed decisions such as using practices and tools for circular construction right from the inception, strategies for integration at all the stages of building, urban mining, use of building codes and action plans, and other environmental and economic benefits. The identified parameters and indicators that help bring circularity in the built environment can be used by architects, planners, engineers, contractors, and policymakers to devise solutions for responsible resource consumption and production in the construction industry by extending the utility and service life of buildings, mitigating the environmental impact by minimizing the waste, deriving economic benefits through incentives and funds, etc. As the aspects highlighted in the article are interrelated, and the identified parameters and indicators specifically focus on the construction industry, there is further scope for future studies on developing an analytical (applied) framework for the circular economy in the construction industry. The framework can focus on implementing and using circular economy strategies in construction that can be used and replicated in different projects. Development practices must integrate the circular economy approach to address the growing demand for limited resources by applying circular economy initiatives such as R principles and its integration in different stages of building, the use of circularity tools, effective construction and demolition waste management, and circular economy action plan, etc., in the industry which will help create a sustainable built environment.

Abbreviations

EU	European Union
CE	Circular Economy
BIM	Building Information Modeling
C&DWM	Construction and demolition waste management
EoL	End-of-Life

Supplementary Information

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Additional file 1.

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Authors' contributions

RK[1] conceptualized the article, conducted the literature review, defined methodology, analyzed and derived the results, and finally made the conclusions, Writing- Original draft and preparation. MC[2] thoroughly discussed the article through the process and finally did the validation, Writing- Review, and editing. All the authors have read and approved the manuscript.

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