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# Chapter 12
# Circularity Criteria and Indicators at the Construction Material Level

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**Abstract** Circular economy (CE) approaches highlight the potential of construction materials to achieve circularity and sustainability in resource-efficient construction systems and industries. Implementing CE at the material level involves factors such as efficiency, durability, waste reduction through recirculation, and replacement, while

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encompassing criteria that define circularity in building materials. Understanding the inherent characteristics and behaviours of these materials is crucial for maximising their circularity potential. This chapter analyses key properties of traditional construction materials, such as concrete and steel, alongside novel sustainable materials like bamboo, timber, and biomaterials. It identifies and proposes methods to promote circularity at the material level. Additionally, the chapter explores the application of CE principles to both traditional and innovative construction materials. Furthermore, the chapter discusses indicators designed to assess circularity at the material level, serving as valuable tools for informing decision-making and implementation practices in the construction sector. Various types of indicators are presented, categorised as strategic, generic performance, performance, and water consumption indicators. Strategies aligned with waste hierarchy principles are outlined, emphasising the reduction of construction and demolition waste, lowering greenhouse gas emissions, conserving energy, and optimising costs and water resources.

**Keywords** Circular economy · Construction materials · Built environment · Concrete · Low-impact cement · Recycled aggregate

## 12.1 The Significance of Construction Materials in Circular Economy Systems

Circularity of materials' inflows and outflows is essential for achieving a circular economy (CE) in industrial systems. It is grounded in the principle of maintaining products and material circulation through various processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. These strategies minimise waste and promote sustainable resource use by maximising material lifespan. The CE system's objectives include waste and pollution elimination, circulating products and materials at their highest value, and decoupling economic growth from resources use while reducing environmental impacts such as $CO_2$ emissions [1].

Circularity involves redesigning materials, products, and services for reduced resource-intensity and reclaiming "waste" as a resource for new materials and products. It emphasises the use and reuse of materials, optimising resource efficiency, and supporting nature's regeneration. CE is design-driven and based on three core principles: (i) waste and pollution reduction; (ii) circulation of products and materials at their highest value; and (iii) natural systems regeneration. However, the systemic success of CE depends on broader global shifts, such as the transitioning to renewable energy and ensuring a stable supply of responsibly sourced renewable materials [2].

The construction sector significantly contributes to environmental degradation, waste generation, and carbon emissions. In the European Union (EU), building construction consumes 40% of materials and primary energy while producing 40% of annual waste [3]. Buildings worldwide account for 33% of greenhouse gas (GHG) emissions and 40% of energy consumption, stemming from equipment usage, material manufacturing and transportation [4]. In 2009, the construction sector emitted 5.7 billion tonnes of $CO_2$, representing 23% of global economic activity emissions [5].

Globally, construction and demolition waste has reached approximately 2.01 billion metric tonnes per year, as reported by The World Bank. This includes both operational and construction-related emissions, posing significant environmental and climate challenges. However, the sector holds high circularity potential, offering a path to a more sustainable and resilient economy by using construction materials more efficiently and effectively. The CE approach emphasises the importance of construction materials in achieving circularity; involving processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting to extend their lifespan. By prolonging the life of materials and products, CE can reduce the need for virgin resources, minimise waste generation, and foster a more sustainable and resource-efficient construction industry [6].

Construction materials are at the heart of the CE system, as they enable efficiency, waste reduction, decarbonisation, resource conservation, and value creation in the construction industry. Selecting the appropriate building materials and components from the early stages is important to carry out the concept's principles along the value chain and create a closed-loop system [7]. Embracing circularity in the sector can lead to significant environmental and economic benefits, including reduced environmental impact, cost savings, and new business opportunities. To achieve a CE for building materials, several key actions have been identified, including reducing material use, substituting high impact materials with lower impact materials, and recirculating products or materials through reuse and recycling. By adopting these actions, the construction sector can contribute to a more sustainable and resilient economy while minimising its environmental footprint and preserving resources for future generations [6].

In today's world, sustainability has become a paramount concern for businesses and industries across various sectors. With the global population steadily growing, the demand for resources and products is escalating, straining the planet's finite resources and contributing to environmental degradation. This is where the concept of CE steps in as a new paradigm to meet the evolving demands for sustainability and tackle these contemporary challenges. The CE concept has gained prominence on the agendas of many organisations striving for sustainable practices and their integration into operational frameworks. By optimising processes and implementing efficient technologies, companies can significantly reduce their ecological footprint and mitigate the negative impacts associated with resource extraction and consumption environment [8].

Another vital principle of sustainable and circular production is the maximising of product longevity. This entails designing products and assets with durability to withstand wear and tear over extended periods. By advocating for reuse and recycling, organisations can prolong product life cycles, decreasing the necessity for constant manufacturing and cutting down on waste generation. This approach not only conserves resources but also aligns with CE principles, where materials are continuously looped back into the production cycle environment [8].

Enhancing production efficiency is another crucial element of sustainable production. This involves improving manufacturing processes to maximise output while minimising negative environmental and social impacts. By optimising production techniques, reducing waste generation, and implementing cleaner technologies, companies can achieve higher productivity levels while reducing their carbon footprint and minimising harm to local environment and communities [8].

## 12.2 Circularity Criteria for Construction Materials

Multiple collaborative frameworks have been developed to promote a sustainable and circular built environment through the use of circularity strategies in materials [8]. These frameworks encompass: (i) European and national standards and regulations aimed at incorporating recyclable and natural materials; (ii) Tax incentives and financial support for the adoption of recovered, recycled and/or more efficient materials with reduced GHG emissions; and (iii) Differential value-added tax (VAT) rates based on the type of materials used distinguishing between recovered and virgin materials.

However, as the concept of CE is relatively new, further efforts are needed to focus on defining specific conditions and establishing standards to enhance circularity across the various stages of material production, utilisation, and end-of-life management. In this regard, academia and industry are witnessing significant interest in developing innovative materials with lower carbon footprints, aligning with the objectives of CE. In fact, the largest share of the environmental footprint in construction activities is attributed to the use of construction materials [9], with concrete and its primary constituent, cement, contributing the most–as they are the most widely used construction material globally [10].

Mitigation measures for this impact include the exploitation of low-impact cement and supplementary cementitious materials, typically industrial by-products. Exploiting recycled aggregate as a substitute for natural aggregate is another strategy. Replacing part or all of the natural aggregate with recycled aggregates from crushed Construction and Demolition Waste (CDW) is an effective solution aligned with the goals of EU Directive 2008/98/EC and supports CE initiatives. Still, ongoing efforts also address other important construction materials to increase their circularity values including structural steel, timber, plastics, metals and finishing materials. Table 12.1 outlines the most commonly used construction materials and their applications in the industry.

Achieving circularity in materials involves considering different life cycle perspectives across various stages, including acquisition, extraction and procurement, manufacturing, construction, maintenance and repair, recovery and reclamation, and end-of-life management.

**Table 12.1** Construction materials' uses (adapted from Ferrer et al. [8])

| Material | Use |
|---|---|
| Adobe | – |
| Agglomerated cork | Insulation of buildings |
| Alternative plastics | Heating, duct, and drainage systems |
| Aluminium | *E.g.*, windows and other accessories/components |
| Cements:<br>Cement–limestone and clay<br>Ecological cements | Concrete element |
| Concretes:<br>Biological concrete<br>Conventional concrete<br>Conventional reinforced concrete<br>Photocatalytic concrete<br>Recycled concrete | Structures, exterior walls, pavements |
| Fibres | Exterior and interior walls–*e.g.*, sandwich panels |
| Fired clay[a] | Walls–bricks, facades and tiles |
| Paintings | – |
| Plastics | Insulation, pipes–*e.g.*, polyethylene, plumbing and heating installations (polybutylene), membranes |
| Steels | Structures, forgings, electrical cabling, conduit/trunking, ducting, pipework |
| Stone | Structure, exterior and/or interior walls |
| Wood[b] | Pillars, girders, beams, laminated wood walls (industrially treated), finishes |

[a]Heated clay at less than 950°C; [b]Treated, processed, certified and recycled

Numerous studies and research efforts have proposed multiple criteria sets to define circularity in building materials. Morató et al. [11] outlined guiding factors for the CE implementation at the material level in the built environment, as detailed as follows: (1) Efficiency–Reducing material intensity by avoiding over-specification with high-performance materials, notable steel and concrete; (2) Durability–Designing and producing materials for maximum useful life extension, superior to that of buildings and infrastructure; (3) Closing Cycles, Recirculation and Reduction of Waste–Recycling materials at the end of their useful life, *e.g.*, designing for selective disassembly instead of demolition; and (4) Replacement–Substituting materials with high carbon footprint and environmental impact with lower-impact alternatives. Environmental Product Declarations (EPDs) are recommended as relevant step toward circularity considerations at the material-level [12].

Additionally, Rahla et al. [7] suggested a set of CE criteria for building materials and components based on an extensive literature review: (1) Recycled or Recovered

Content–Reducing the input of virgin materials content by partially relying on recycled or recovered waste; (2) Recyclability–The ability of a material to be recyclable through a particular process at its end-of-life (EoL); (3) Reusability–The capability of materials to be reusable at their EoL, providing building elements with a second life; (4) Ease of Deconstruction–Selected materials facilitating different design strategies for reversibility, such as adaptability and disassembly with minimal damage; (5) Maintainability–Characterising materials and components that can remain in use through maintenance, repair, and refurbishment; (6) Durability–Resistance of materials and components to deterioration over time while meeting minimum requirements; (7) Energy Recoverability–Potential for converting building materials and components into energy through incineration; (8) Upcycling Potential–Reintroducing materials and components into the loop for higher value; and (9) Biodegradability–Ability of building elements to disintegrate in the natural environment with no ecological damage.

These CE criteria encompass three main facets: (i) type of input; (ii) performance during the use phase; and (iii) EoL processing. The type of input is characterised by a single criterion–recycled or recovered content–indicating the utilisation of materials recycled or recovered from other sources in the manufacturing of new construction materials. An essential consideration in this context is the recovery method employed, the process, and the application of the reclaimed material, which define the level of relevance to CE based on its position in the waste hierarchy. The efficiency of the recycling process, leading to usable recycled content, is an important consideration; however, it is contingent upon the system boundary.

The use phase introduces durability and maintainability as critical criteria, advocating for building materials and components with the potential for longer service life. EoL processing scenarios include the remaining CE criteria –recyclability, reusability, ease of deconstruction, upcycle potential, biodegradability, and energy recoverability–to avoid landfilling.

Supplementary CE criteria, such as toxicity, embodied energy (EE), and local availability, warrant examination. Material toxicity refers to the release of harmful chemicals or ingredients during the production or EoL, which can directly or indirectly impact the environment negatively [13]. The EE of building materials quantifies all energy expended throughout material production, from resource extraction to final manufacturing processes, transportation, and construction, expressed in MJ/kg and convertible to carbon emissions equivalence (kg $CO_2$e/kg). The EE criterion may hold greater relevance for environmental sustainability, depending on how sustainability and circularity concepts are distinguished and intertwined, and considering the overlaps in stakeholder usage. Local material availability significantly affects cost, environmental factors and construction schedule. Distant materials incur high transportation costs and elevated EE, potentially leading to project delays if orders are not placed well in advance.

The classification of commonly used building materials according to chosen CE criteria of reusability, recyclability, EE, and toxicity is presented in Table 12.2 These selected criteria are part of the EoL group, and simultaneously, address the input group.

**Table 12.2** Classification of commonly used building materials according to chosen CE criteria (adopted from Akhimien et al. [13]; Hammond et al. [14]; Pacheco-Torgala and Jalali [15])

| Material | Reusability | Recyclability | EE (MJ/kg) | EE-$CO_2$ (kg $CO_2$e/kg) | Toxicity[a] |
|---|---|---|---|---|---|
| Stone (aggregate) | Yes | Yes | 0.083 | 0.0048 | No |
| Stone (limestone block) | Yes | Yes | 0.850 | – | No |
| Fired clay bricks and blocks | Yes | Yes | 3.000 | 0.1240 | No |
| Fired clay roof tiles | Yes | Yes | 6.500 | 0.4500 | No |
| Structural concrete | No | Yes | 1.111 | 0.1590 | No |
| Structural timber | Yes | Yes | 8.500 | 0.4600 | No (Yes in use phase, if treated) |
| Structural steel | Yes | Yes | 20.100 | 1.3700 | No |
| Aluminium | – | Yes | 155.000 | 8.2400 | No |
| Glass | No | Yes | 15.000 | 0.8500 | No |
| Gypsum board | No | Yes (100%) | 6.750 | 0.3800 | No |
| Plastics (PVC, polyvinyl chloride) | No | Yes | 77.200 | 2.4100 | No, but has fire toxicity |
| Expanded polystyrene (EPS) insulation | No | Yes | 88.600 | 2.5500 | No, but has fire toxicity |
| Glass wool insulation | No | Yes | 28.000 | 1.3500 | No, but has fire toxicity |
| Rock wool insulation | No | Yes | 16.800 | 1.0500 | No, but has fire toxicity |

[a] Toxicity data are not concerned with building materials that contain industrial by-products and waste materials; *i.e.*, phosphogypsum, some blast furnace slags, and some fly ashes…

Plastics are known for their resistance and lightness. Fibre panels offer flexibility in changing use and saving space; *e.g.*, fibres from recycled cellulose paper have properties similar to wood. When treated with borax salts, they acquire fire retardant, antifungal and insulating properties [8]. Steel is more efficient at supporting loads compared to concrete. The use of Ultra High-Performance Concrete (UHPC) enhances long-term durability performance and materials efficiency, making it suitable for various applications, including extreme environmental conditions such as coastal areas.

To facilitate the reuse and recycling of components and materials from demounted structures, Cai and Waldmann [16] proposed the establishment of a material and component bank, based on extensive literature reviews and analyses. Their study highlighted the potential for such a bank to contribute to a more sustainable and circular built environment.

For these purposes, understanding the inherent characteristics and behaviours of common building materials is crucial to maximising their circularity potential by creating suitable pathways for recovery, reuse, and recycling while adhering to waste hierarchy principles. Table 12.3 outlines the recovery, reuse, and recycling characteristics of common construction materials.

### *12.2.1 Traditional Construction Materials*

Traditional building materials offer certain advantages in terms of durability and maintainability, benefiting from extensive use in the construction sector over an extended period, resulting in well-understood properties. Additionally, these materials often possess the advantage of local availability, aligning with circularity principles.

Ensuring the satisfactory durability of building materials requires adherence to specific conditions: (i) appropriate design tailored to the environmental context–*i.e.*, during the design phase and (ii) meticulous manufacturing, installation, and, if necessary, curing, with stringent quality control measures–*i.e.*, during the construction phase. Meeting these conditions allows built-in materials to retain their properties throughout their service life without necessitating radical investments for upkeep. The degree of deterioration or damage in traditional building materials determines subsequent utilisation scenarios after the EoL phase. Potential scenarios include reuse, recovery, recycling, and the least favourable, disposal.

**Concrete**. As the most commonly used anthropogenic building material, consists of a matrix, typically hardened cement paste, and filler (aggregate). Its versatility arises from the broad range of applications in binders and aggregates, resulting in an extensive array of concrete types. The ability to combine various component materials allows for an almost unlimited array of concrete variations, establishing it as a universal building material with diverse applications. However, when the term "concrete" is used, it typically refers to structural material such as plain, reinforced, and pre-stressed concrete.

The basic properties of ordinary concrete closely resemble those of natural stone. These properties include high compressive strength, low tensile strength, brittleness and tendency to crack, relatively high modulus of elasticity, relatively high unit mass, relatively low thermal conductivity, dimensional stability, durability, satisfactory chemical inertness and low embodied carbon (per unit mass) [17]. Some of these properties significantly limit the structural application of plain concrete, leading to the practical use of reinforced and prestressed concrete types. Concrete exhibits specific properties, including high shaping potential, shrinkage over time, creep under load, and prone to carbonation. These properties together with the basic ones should be thoroughly analysed to identify appropriate methods for fostering circularity in this essential construction material.

**Table 12.3** Construction materials and their characteristics towards implementing CE in the built environment (adapted from Ferrer et al. [8])

| Material | Characteristics and recycling, recovery and reuse potential |
|---|---|
| Adobe | Limited bearing capacity. Brings benefits for the environment, such as: low energy consumption and pollution, insulating properties, local character |
| Agglomerated cork | Good thermal and acoustic insulation capacity, fireproof, absorbs moisture. Natural product–cork oak logging is not demanded |
| Alternative plastics | Inert, sterilisable, not containing chlorine–as toxic material, and recyclable. Polypropylene, polybutylene, polyethylene are usable thermoplastic alternatives |
| Aluminium | Highly recyclable |
| Cements:<br>Cement–limestone and clay<br>Ecological cements | High energy manufacturing cost. There are different solutions; much less emissions are produced when a mixture of blast furnace slag, term waste and chemical and organic additives are used |
| Concretes:<br>Biological concrete<br>Conventional concrete<br>Conventional reinforced concrete<br>Photocatalytic concrete<br>Recycled concrete | Its main characteristic is the ability to grow plant organisms on its surface, by accelerating the growth of fungi, microalgae and mosses that absorb $CO_2$. High energy manufacturing cost; it is not a good insulator. High energy manufacturing cost; additives with polypropylene fibres, which improve the flexion in pavements and the concrete resistance; accelerator additives. It produces a decontaminating effect, thanks to the addition of titanium oxide nanomaterials; it is especially designed to be used in outdoor elements in urban areas with high levels of pollution–*i.e.*, polluting agents such as carbon dioxide, nitrogen oxides or sulphur oxides; the incidence of sunlight and temperature are factors that favour photocatalysis against pollution. It can be made from rubble by adding up to 20% in reinforced concrete for new construction; recycled aggregates increase |
| Fibres | "Dry" construction is possible, saving water. Different recyclable solutions based on vegetable fibres, cement residues and petrochemical derivatives |
| Fired clay | Good thermal inertia, absorbs moisture. Recyclable |
| Paintings | From diverse compositions being most of them derived from petroleum. Ecological types by replacing hydrocarbons with natural components |
| Plastics | Very effective for insulation. Environmentally friendly options as an alternative to PVC (polyvinyl chloride) |
| Steels | Highly recyclable; high energy cost of extraction and transformation; more efficient at supporting loads than concrete; "dry" steel frame construction does not consume water on site |

(continued)

**Table 12.3** (continued)

| Material | Characteristics and recycling, recovery and reuse potential |
|---|---|
| Stone | Impact on the landscape in the extraction phase; high transportation cost; very long-lasting material; recommended in construction respectful of local tradition |
| Wood | It comes from renewable sources that in turn absorb $CO_2$; it is recyclable; it is ecological if it comes from certified forests and if sawmill waste is reused for laminated panels–*e.g.*, waste OSB boards (layers of aligned chips and chips) |

The implementation of CE principles in concrete can be interpreted across three distinct scales, as proposed by Marsh et al. [18]: (1) Material-scale; (2) Product-scale–*i.e.*, structural elements and buildings themselves; and (3) System-scale–*i.e.*, the cement, concrete and construction industries.

This section aims to discuss the potential for implementing CE principles in concrete at the material scale. To gain a comprehensive understanding of how CE strategies can be integrated into concrete at this level, it is crucial to take into account the following factors, as outlined by Marsh et al. [18]:

(1) Cement and concrete productions are essentially chemically irreversible processes. Clinkerisation in Portland cement production and the hydration reaction for setting Portland cement-based concrete involve complex chemical reactions with several phase transformations, which are essentially irreversible.
(2) Cement production exhibits chemical versatility. There is a considerable degree of chemical flexibility in producing cement that fulfils the required characteristics. Tailoring the composition and feedstock materials offers significant opportunities to drive down the cradle-to-gate embodied carbon and energy of cement. Moreover, a wide range of different resources, including industrial by-products and wastes, can be used for production.
(3) Concrete production has the capability to use a wide variety of materials as aggregates. This diversity is advantageous from the CE perspective and can even enhance certain physical properties of concrete. Potential sources for aggregate substitution include industrial by-products such as coal bottom ash and blast furnace slag; CDW like "old" concrete and fired clay bricks; waste materials such as glass and rubber, and bio-based materials like hemp, wood and fabric fibres. The possible implementation of CE criteria, classified in the aforementioned phases–*i.e.*, type of input, the use phase, and the EoL scenario–, is briefly analysed on concrete [18].
(4) Reusability (EoL scenario)–Implementing the criterion of reusability at the material scale for concrete is not feasible. It becomes achievable only at the product scale if the structure is designed for easy dismantling of concrete elements, *e.g.*, concrete precast elements such as blocks and roof tiles; and components, *e.g.*, prefabricated beams, columns, walls and slabs.
(5) Recover (EoL scenario)–Concrete cannot fulfil this criterion due to its chemical irreversibility, preventing its return to basic component materials. The cement

matrix is completely chemically irreversible, meaning that hydrated cement paste cannot be reverted back to cement and water. However, there is a possibility of returning aggregate to its initial state (natural aggregate) through chemical, thermal or mechanical procedures, albeit these methods are environmentally harmful or energy intensive.

(6) Recyclability (EoL scenario)–At a material level, the most viable solution is recycling old concrete into aggregate. Recycled concrete aggregate (RCA), however, has limited application compared to natural aggregate due to its inferior characteristics and wide variations in quality. Additional treatment, such as heat or carbonation treatment, is often required for RCA to be usable. It is important to note that RCA usually represents a down-cycling process, placing it at the bottom of the waste hierarchy in CE principles. Nonetheless, RCA can also exemplify a recycling process. For instance, the production of Coarse RCA of satisfactory quality is effectively used as a substitute for natural aggregate in concrete production (recycling), while lower-quality RCA serves as base and sub-base material (down-cycling). Fine RCA, however, has very limited application due to its specific properties.

(7) Reduce (input phase)–At a material scale, several strategies can be implemented: (7.1) Decrease the cement content in concrete production by optimising concrete mixture. This can be achieved through increasing the amount of inorganic additions, such as nearly inert additives, pozzolanic or latent hydraulic additions, using superplasticisers, and increasing aggregate content; (7.2) Reduce clinker content in cement production by incorporating industrial by-products as supplementary cementitious materials; (7.3) Decrease natural aggregate content in concrete by substituting it with different types of recycled materials; (7.4) Minimises clean water usage by relying on washed water and superplasticisers. At a structural scale, reductions in concrete volume can be achieved by using high-performance concrete (HPC) or high-strength concrete (HSC) instead of conventional concrete, as well as by optimising structural elements' cross-section design, such as employing T-section instead of rectangular section.

(8) Durability (input phase)–Increasing durability and hence, extending structural longevity is a crucial design-stage strategy to slow resource flows by prolonging the technical lifespan of components and products. In the context of concrete, achieving durability involves strategies at both the material and product scales to ensure concrete's resilience in a given service environment. At the material scale, these strategies encompass assessing environmental influences that may compromise concrete durability. This assessment guides the selection of appropriate cement types and the design of concrete mixes that strike a balance between initial cost and resource efficiency *versus* longevity. Implementing these measures not only extends service life but also reduces the consumption of concrete needed for replacement structures, thereby enhancing the reuse potential for concrete components. Given the significant concrete consumption, it is essential to pay attention to the reduction of $CO_2$ emission during the design phase, despite concrete being a material with low embodied carbon.

(9) Maintenance (use phase)–Maintenance, refurbishment, repair and replacement, all fall within the use phase and represent strategies for slowing down resource flows by extending the technical lifespan of used material, and consequently of products and components. In the context of concrete, these strategies vary in interpretation depending on whether they pertain to buildings, infrastructure, or industrial facilities, as well as the nature of the service environment exposure: maintenance involves the general upkeep of structures and refers to preventing material damage occurrence through planned and unpredicted measures–*e.g.*, by applying protective coatings on exposed surfaces; and refurbishment entails repairing limited damage of concrete, reinforcement, etc., within a concrete element or replacing a damaged element with a new one.

**Structural and Concrete Reinforcing Steel**. Steel is one of the world's most important engineering and construction materials, finding application in nearly every facet of human life, from automobiles and vessels to household appliances and utensils. It stands as the third most commonly used building material, following concrete and cement. Structural steel, a man-made material, comprises up to 98% iron, with carbon, silicon and manganese serving as the primary alloying elements. Key properties of structural and concrete reinforcing steel include high tensile strength, hardness, ductility, toughness, a high modulus of elasticity, weldability, substantial unit mass, high thermal conductivity, dimensional stability, low corrosion resistance, low fire resistance, and a high embodied carbon (per unit mass) content. Structural steel coasts impressive CE credentials. As a material, it embodies strength, durability, versatility, and recyclability. As a structural framing system, it embodies characteristics such as being lightweight, flexible, adaptable and reusable. The amalgamation of strength, recyclability, availability, versatility and affordability positions steel as an exemplary structural material, holding great potential for implementing CE strategies.

The versatility of structural steel extends across its metallurgical and chemical composition, as well as its utility as a construction product and structural framing system. Firstly, steel is infinitely recyclable, ensuring sustainable and circular practices in its lifecycle. Secondly, structural steel products are durable, robust and dimensionally stable elements; typically assembled through bolting, making them inherently demountable and reusable. Lastly, steel structures offer ease of extension and reconfiguration on-site, thereby prolonging building lifespans.

(1) Reusability (EoL scenario)–Structural steel sections are inherently reusable. The concept of reusability, in contrast to the current common practice of recycling structural steel through re-melting, offers significant potential, in terms of resource efficiency and carbon emission savings. Structural steel reuse generally occurs in three main ways: (1.1) *In-situ* reuse, in which the steel structure (frame) is reused, with or without alterations; (1.2) Relocation reuse, which involves deconstruction of an existing steel structure, that is then transported and re-erected, generally in its original form, at a different location for the same or similar purpose; and (1.3) Component reuse, which involves careful deconstruction of an existing structure where individual structural steel members are reclaimed and used to construct a new permanent structure. Steel can be reused

multiple times without comprising its metallurgical properties, thus maintaining its performance characteristics.

(2) Recycling (EoL scenario)–Steel is 100% recyclable without any loss of its inherent material properties, making it the most recycled industrial material worldwide, with over 650 million tonnes recycled annually. Steel comprises two primary components: iron ore, one of the Earth's most abundant elements, and recycled (scrap) steel. Using scrap as the primary input is preferred over iron ore due to its cost-effectiveness, conservation of resources, and lower energy consumption. However, maintaining the quality of newly produced steel is crucial. Achieving the right balance between its two primary components, fresh iron ore and scrap steel, is essential for producing high-quality steel. It is argued that good-quality steel requires fresh iron ore in its composition, as scrap steel alone cannot maintain the quality of produced steel. Theoretically, all new steel could be produced from recycled steel. However, this is not currently feasible because the global demand for steel exceeds the supply of scrap. This imbalance is attributed to steel's widespread popularity and exceptional durability; with an estimated 75% of steel products ever manufactured still in use today.

(3) Longevity (input phase)–Achieving longevity involves designing buildings to be more flexible and adaptable to change, facilitating deconstruction and reuse, and implementing appropriate maintenance plans. Steel structures can be enhanced for flexibility and adaptability through three key principles: (3.1) Structural extension, vertically or horizontal, to accommodate changes in use or owner requirements; (3.2) Internal flexibility to accommodate varying uses, work patterns, or tenant/owner needs; and (3.3) Flexible building services to enable servicing upgrades or change of building use without impacting the structure. Designing for decomposition hinges on two crucial factors: the type of materials and components used, with products like structural steel offering higher reusability compared to other structural materials and systems; and the method of connection between materials and components–possibility of parsing. Steel stands out as one of the most robust construction materials, suitable for a wide range of projects from skyscrapers to bridges. A well-designed steel structure can last 50 to 100 years with minimal maintenance. However, despite its durability, regular maintenance is essential to extend its lifespan. Protective coatings like paint are commonly applied to steel elements to guard against corrosion, while protective foams have been used to provide a level of fire protection, with intumescent coatings tending now to be used. Proper processing and maintenance are crucial as steel structures can incur higher maintenance costs if corrosion sets in. Additionally, periodic touch-ups such as repainting contribute to maintenance expenses over time.

(4) Embedded Concrete Reinforcing Steel (EoL scenario)–Upon reaching the end of their service life, reinforced concrete structures primarily follow a CE strategy for their embedded reinforcement: recycling. Separating concrete from reinforcement involves invasive methods that often damages and deforms the steel rods rendering them, unsuitable for reuse. Once the steel bars are extracted from

concrete waste, they are collected in scrap yards and subsequently re-melted in furnaces.

### 12.2.2 Novel Sustainable Construction Materials

Collaboration within value chains, as an industrial symbiosis strategy, represents a critical step towards transitioning to a CE within the built environment [8]. Embracing this approach, sustainable value chains can foster projects aimed at developing sustainable materials through collaborations with other sectors. For instance, recycled polyurethane and textile fibre coatings can be repurposed as raw materials for pavement products. In this context, numerous innovative materials have been proposed, incorporating novel ingredients to enhance their performance while promoting circularity. This includes integrating waste materials from other industries, reusing secondary materials, and encouraging the use of bio-based materials.

Bamboo holds great potential for use in green building concepts due to its sustainable sourcing and minimal environmental impact [19]. Wood is a well-known material in green building construction. Various engineered wood-based panels, including oriented strand board (OSB), solid wood, particleboard, medium density fibreboard (MDF), or plywood are commonly used for non-load-bearing purposes in building and interior applications. Moreover, structural composite lumber and timber such as glulam, laminated veneer lumber (LVL), parallel strand lumber (PSL), oriented strand lumber (OSL), and cross-laminated timber (CLT) are gaining popularity and widespread acceptance among stakeholders, including architects, engineers, and building experts worldwide.

However, Ahn et al. [20] revealed a substantial knowledge gap within the mass timber industry regarding implementation of CE principles. They emphasised the importance of researchers and the industry professionals sharing knowledge on the circularity of the structural wood composites. Wood cement boards, produced by incorporating natural fibres, wood particles or wool as fillers into cement matrix, provide lightweight, thermal insulation, acoustic performance, and other beneficial sustainable solutions for cementitious building materials [21].

Biomaterials derived from plant and animal extracts, often sourced from by-products and waste materials, offer promising avenues for reducing the environmental impact of the construction industry. Unlike synthetic additives, commonly used in cement-based materials for setting retarders and plasticisers, organic additives pose a lower environmental impact. These alternatives, such as extracts from plants and animals, can enhance the setting properties of mortars while promoting environmentally conscious material usage.

One notable example is the use of prickly pear (*Opuntia ficus-indica*, OFI) mucilage extract, a plant-derived additive with demonstrated efficacy in mortar and concrete applications across various regions, including Meso- and South-America. The scientific rationale behind these additives lies in the hydrating properties of the mucilage polysaccharide complex found in OFI extracts. Aquilina et al. [22] have explored different forms of OFI extracts, incorporating them into cement pastes and mortar mixtures by substituting water with OFI mucilage or cement with OFI lyophilised powder. The findings indicate that incorporating OFI additives in cement-based mortars enhances strength when replacing water and powder components, albeit resulting in slightly lower strength in cement pastes. Moreover, the inclusion of OFI additives extends the setting time for both water and powder replacements, suggesting their potential as retarding agents in cement-based materials [22].

The potential use of *Agave sisalana* fibres in self-compacting concrete (SCC) and their impact on fresh properties, early age characteristics and hardened properties of concrete, have been investigated by Calleja and Borg [23]. Their study delved into the effects of different fibre lengths, specifically 15, 25 and 35 mm, and varying fibre volume percentages of 0.25, 0.5 and 1% to evaluate concrete performance across different parameters. Fresh concrete properties indicated that the introduction of fibres in the concrete mix reduced its self-compacting characteristics, primarily in terms of passing ability, although the SCC still maintained significant flow characteristics overall. Concrete and mortar underwent controlled environmental conditions within an environmental chamber, while mortar panels were exposed to high air flows for testing. The results indicated that adding agave fibres led to a decrease in plastic shrinkage crack widths and delayed crack formation. Additionally, the restrained concrete ring test demonstrated higher strains exerted on the steel ring with higher fibre percentage. Notably, the addition of fibres resulted in decreased density, ultrasonic pulse velocity, and compressive strength of the concrete, yet led to enhancements in flexural peak load and tensile splitting strength [23].

The poultry production industry is a significant agricultural activity with economic importance, but it generates substantial waste, including large quantities of feathers that pose disposal challenges. One option is as reinforcement in cement-based construction materials, such as low-impact concrete, addressing the principles of CE. Feathers have been utilised in various forms in construction materials, including whole fibres, hand-cut rachis, ground fibres, and combinations of these forms. Feather fibre cement-based materials have been applied to create feather-board, a cost-effective material suitable for non-structural applications. Studies on feather fibre cement-based materials have explored their mechanical characteristics, setting time, and hydration properties. In a study by Borg et al. [24], the potential use of feather fibres in cement-based materials, including self-compacting concrete, was investigated, focusing on their impact on fresh properties, early age characteristics, and hardened properties, including mechanical and durability aspects. The introduction of fibres in the concrete mix led to a reduction in the workability and self-compacting characteristics. The influence of the bio-polymer fibre in concrete was observed to influence the plastic shrinkage cracking in the environmental chamber and the strain in the concrete ring test. The addition of fibres also improved the mechanical properties including the compressive strength, among other indicators. The research confirmed the potential of the exploitation of waste feather fibres as reinforcement in concrete, supporting circularity in both the agricultural and construction sectors [24].

## 12.3 Circularity Indicators at the Material-Level in Buildings

Indicators and measures hold significant importance in tracking progress towards a CE [25]. Indicators are commonly used to represent complex phenomena or aspects that lack conventional units of measurement. These indicators serve as valuable tools for informing and influencing decision-making and implementation processes. However, it is essential to note that the ultimate responsibility for making these decisions rests with managers, who rely on their value judgments [26]. This section delves into different types of indicators designed to assess the circularity of construction materials. The study categorises these indicators into four groups: (1) Strategic indicators based on Material Flow Analysis (MFA); (2) Generic performance indicators for assessing material circularity in industrial products; (3) Performance indicators to measure construction material circularity; and lastly (4) Water consumption indicators.

### *12.3.1 Strategic Indicators Based on MFA*

The process of MFA involves examining inputs, processes, and outputs within a production activity or industrial sector, covering the entire value chain. This includes raw material production, production processes and operations, and waste management [27]. The Economy-Wide MFA method, used by Eurostat and adopted by the statistical offices in EU countries, is instrumental in measuring circularity at the country level.

Figure 12.1 illustrates the construction material flow at a country-level perspective, specifically focusing on CDW associated with the industry across the entire value chain of the focus sector. The Fig. 12.1 depicts stages that highlight the main material flow, starting with the construction stage, followed by energy flow and waste flow for CDW.

A deductive top-down approach is required for all stages, derived from macroeconomic national statistics. However, obtaining proper and accurate data for the last stage–CDW from the construction sector at the country or EU level–may pose high uncertainties. Therefore, a "bottom-up" method can be utilised for the last analysis stage. This method first analyses the CDW, reuse, and recycled flow in typical construction activities based on date from construction companies and then extrapolates the results to the national construction sector.

In-depth knowledge and data on material flow, stocks, and quotas can be obtained from literature and national stakeholders. This information is analysed and disaggregated to provide appropriate CE action options that guarantee tangible impact improvements of the focus sector. Particular attention is required to explore the self-supply potential of the sector through the reuse and recycling potential of construction materials.

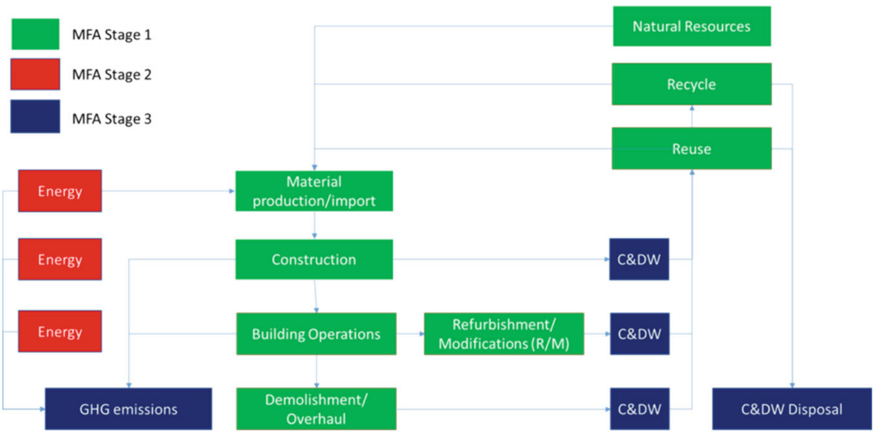


**Fig. 12.1** Resource flow cycle at a country-level construction sector

The construction material flow system analysis for the construction sector includes two main streams: construction activities related to buildings and infrastructures. Each of these subsectors includes material flows associated with new constructions, refurbishment/modifications (R/M), and demolition/overhauling old buildings and infrastructure. The system also encompasses material flows linked to raw material extraction, material recycling, waste treatment, and CDW deposition. Figure 12.2 provides an overview of material flows for buildings and infrastructure related activities.

In MFA Stage 2 (see Fig. 12.3), the energy flow analysis of the construction sector focuses on energy usage for materials production and its associated GHG emissions.

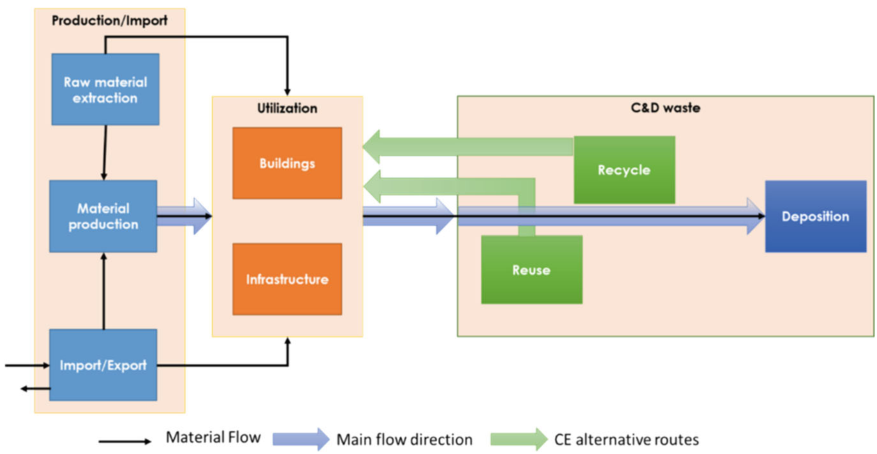


**Fig. 12.2** Material flow directions for buildings and infrastructures' construction activities

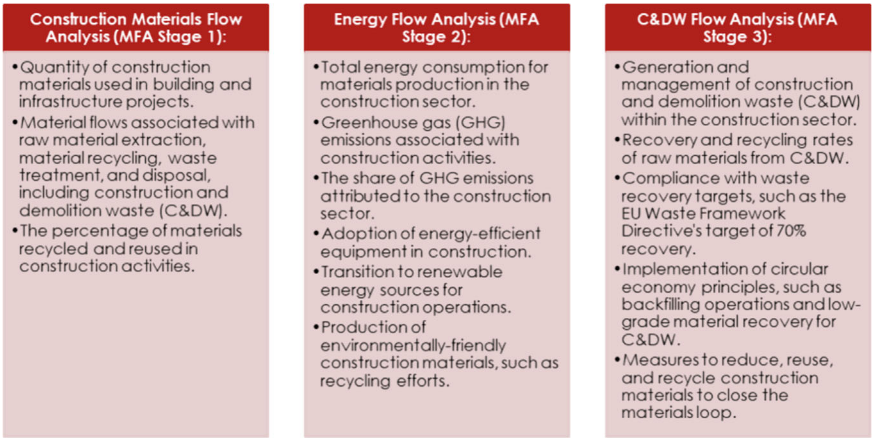


**Fig. 12.3** Strategic indicators for MFA in the construction sector

As signatories to the United Nations Framework Convention on Climate Change (UNFCCC) ratification, countries are required to reduce GHG emissions by at least 15% from 2021 to 2030 compared to 1990 levels [28]. Notably, the construction, manufacturing, and energy industries collectively contribute approximately half of all GHG emissions. Specifically, the construction industry's GHG emissions share stabilised at 13% in 2017 [29]. Implementing practices like recycling construction materials and transitioning to renewable energy sources can effectively manage GHG levels. Key future strategies for reducing GHG emissions in the construction sector include adopting energy-efficient equipment, switching to renewable energy sources, and promoting the use of environmentally friendly construction materials.

In Stage 3 (see Fig. 12.3), the building and construction industry generates a large solid waste stream, categorised as CDW. Effective management and recovery of raw materials from this waste can meet a significant portion of supply needs. CDW exhibits a high potential for circularity through backfilling operations and low-grade recovery processes. To prolong the utility of products, components, and materials while retaining their value, it is essential to implement measures to reduce, reuse, and recycle materials within the construction sector. The EU Waste Framework Directive aimed to achieve a 70% recovery rate for CDW by 2020. Several member countries have not only met but surpassed this target. For example, Malta successfully increased its recovery rate from 16 to 100% in just two years, while Greece achieved full recovery of non-hazardous CDW through backfilling. However, variations in quantification methods pose challenges in accurately comparing CDW recovery performance across European member states [30]. Diverse waste coding systems and differing interpretations of terms like "backfilling" further hinder cross-country comparisons of EU-published recovery rates. The Netherlands, for instance, has reached a CDW recycling rate of 95% since 2001, albeit with a negligible portion devoted to recycling. Consequently, it faces challenges related to oversaturation of low-quality road base aggregate in the aggregates market [31]. Effective and monitored CDW management are essential for achieving sustained success. Figure 12.3 summarises the strategic indicators for MFA in the construction sector based on the provided analysis.

The analysis of the construction sector and practices among construction companies, as studied by Turkyilmaz et al. [32], revealed that recycling and reuse are key circular actions that can greatly improve the management of CDW in many countries. The adoption of Industrialised Building Systems (IBS), such as prefabricated materials, can significantly reduce waste generation while improving the quality of leftover and dismantled materials for reuse and recycling. This approach aligns with the "design for disassembly" principle, facilitating easy material separation and reassembly. Legislative measures can play a crucial role in encouraging the use of IBS.

Materials like asphalt, timber, and metals, widely used in construction, hold significant potential for high-value recovery. Asphalt is fully recyclable, making it a favourable choice for effective CDW management. Properly separated wood can also be readily recycled or used for energy recovery. Metals such as steel, aluminium, copper, lead, and zinc can be sold to third parties for recycling. These high-value materials offer significant opportunities for CE improvements through business-to-business reimbursement systems. Effective management of these materials can foster symbiotic relationships for local industries.

However, the construction sector faces several barriers in enhancing circularity in CDW management. Construction companies often lack expertise and best practices in this area and may not have strong relationships with recycling firms. High waste management costs, limited inclination to reuse CDW materials, and a lack of consistent waste management vision also pose significant barriers. Price competition and uncertainties regarding the quality of recycled materials further hinder the adoption of CE thinking. Additionally, the absence of reliable data on the quantity and composition of CDW material streams presents a general restriction for sectoral analysis. Overcoming these barriers and implementing new policy measures are essential to effectively promote the adoption of circular economic thinking within the construction sector.

### *12.3.2 Generic Performance Indicators for Assessing Material Circularity in Industrial Products*

Numerous generic indicators have been developed within the CE context to assess material and product circularity across various sectors, including their potential application in construction materials. These indicators encompass diverse paradigms, categorised into burden-based and value-based approaches, to measure circularity [33] by enhancing the eco-efficiency of a certain system. They predominantly focus on closing and slowing material loops and promoting waste hierarchy. Burden-based indicators evaluate how burdens compare to one another, such as the ecological footprint [34] and the eco-indicator 99 [35]. In contrast, value-based indicators gauge the extent to which one use generates more value than an alternative, as articulated by Figge [36] and Franklin-Johnson et al. [26]. The following sections highlight some prominent indicators addressing the circularity of industrial materials and products.

**Resource Potential Indicator (RPI)**. In the quest for value-based indicators within the framework of the CE, Park and Chertow [37] introduced the RPI. The RPI operates within a resource-based paradigm, providing insights into the technical feasibility of waste reuse, before considering market conditions. This perspective treats waste as a potential resource, contingent on knowledge of where and how it can be redirected for reuse. Notably, the RPI does not hinge on material composition or the physical and chemical attributes. Rather, these aspects are regarded as contingent on technological advancements. In essence, the more components that can be reclaimed using available technologies, the greater the potential for reuse, and vice versa. Factors such as toxic material composition, escalated costs, and complexity can constrain the prospects for reuse, thereby reducing the RPI values. Given the perpetual evolution of technological solutions for material recovery, the potential for reuse naturally grows over time. The RPI calculation is inherently dependent on the existing technological landscape, rendering it context-dependent, subject to local and regional variables like material quality and technological development levels [37]. The RPI employs a quantitative methodology to grapple with the intricacies of products and materials, considering changes in their composition. This approach facilitates decision-making aimed at optimising resource utilisation and reducing waste generation, based on technical feasibility. The computed result is a value ranging from 0 to 1, symbolising the material's utility. A value of 0 indicates that all materials are discarded as waste, while a value of 1 signifies that all materials are ripe for reuse as resources. The resulting value encapsulate the percentage likelihood that a material can be repurposed, and the complementary percentage represents the likability of a material to be treated as waste. To calculate the RPI, the following Eq. (12.1) is used:

$$RPI = a \Big/ b \tag{12.1}$$

where $a$ represents the economically reusable portion of a material utilising available technologies, and $b$ signifies the current level of generation. Both $a$ and $b$ are quantified in mass units [37]. Despite the value of the RPI in addressing crucial circularity aspects, it comes with notable limitations that require user awareness for informed decision-making. These limitations encompass the need for extensive technical data for accurate calculations, as well as economic considerations such as price fluctuations, market applications, and transportation costs that fall outside the purview of the calculation methodology. It is worth noting that the RPI primarily gauges the maximum potential for material reuse from a technological perspective, which often surpasses the real reuse rate influenced by market dynamics. Therefore, integrating updated market analyses can provide valuable insights to complement the RPI results [37].

**Material Circularity Indicator (MCI)**. Another example on value-based circularity indicators at material level is the MCI, co-developed by the Ellen McArthur Foundation [38] and Granta Design [39]. The MCI serves as a comprehensive tool to assess material flows and restorative values associated with a product or a company. It operates on the principle that optimal circularity is attained when 100% of material input comes from renewable sources (non-virgin), and 100% of the output is reusable. Consequently, the MCI provides a numerical representation of a product's or material's circularity, ranging from 0 to 1. The MCI takes into account three critical criteria: the mass of virgin raw materials used in production, the mass of waste that cannot be recovered from the product, and a utility factor that considers the product's usage duration and intensity. The parameters used to compute the MCI encompass: (i) the destination after use, distinguishing between the percentages of recycling collection rate (RCR) and reuse rate (ReR); (ii) the percentage of recycled feedstock (RC); (iii) the efficiency of the recycling process; and (iv) the utility during the use stage, which pertains to the product's usage intensity compared to the industry average. To calculate the MCI, one can utilise an Excel spreadsheet, inputting data such as the percentage of recycled and reused materials, along with information about the recycling process efficiency and the product's functional performance and lifespan relative to industry standards. The MCI is designed to be applicable at both material and product assessment levels, recognising that the conditions for circularity can vary between these two domains. Assessing product circularity is notably more intricate than evaluating material circularity, primarily because products often comprise multiple materials with varying interfaces which constrain the efficiency of the recycling and lead to challenges in separating materials, resulting in increased waste production. It is worth noting that the MCI does not directly account for the complexities associated with material separability and the consequences of incorporating multiple materials irreversibly within complex products. To complement the MCI, the Ellen MacArthur Foundation [38] and Granta Design [39] have developed additional risk and impact indicators that consider factors such as toxicity, scarcity, value chain risks, and energy.

**Longevity Indicator (LI)**. Numerous indicators are dedicated to the idea of slowing down the resource loop to achieve a CE, where time serves as the primary unit of measurement to assess how extensively resources can be utilised before recycling or disposal becomes necessary. One such indicator is the LI, as introduced by Franklin-Johnson et al. [26]. The LI is a value-based metric designed to gauge the contribution to material retention based on the duration a resource remains in active use, with the goal of extending its value for as long as possible. This retention concept is fundamental in maximising resource utilisation within a given product system, encompassing both product use and reuse, as well as materials recycling. The LI quantifies the average lifespan of product and material usage within a product, spanning from initial use to the end of its life cycle. Essentially, the indicator comprises three core components: the initial lifetime, the duration earned through refurbishment, and the time earned through recycling. While these components represent a minimum cycle, additional cycles can be incorporated by continuously modelling directional events. However, it is worth noting that since the longevity indicator is of a generic nature, it necessitates the prior modelling of the specific product system before the calculation can be applied [26]. The LI provides a clear expression of the longevity of individual resources. When determining the longevity of a bundle of resources, these values should be aggregated. By factoring in the three key longevity drivers–product use, refurbishment, and recycling–the LI supports decision-making and performance evaluation regarding materials and products within the context of the CE. Its aim is to encourage longer product lifecycles, increase returns from initial and secondary uses, and the selection of the most efficient recycling processes available. Nevertheless, it is important to note that the LI does not account for the efficiency of recycling or the intricacies of refurbishment in its calculation. Instead, it solely considers the proportion of the product that undergoes refurbishment or recycling. Furthermore, the LI does not align with the waste hierarchy by assigning more weight to the refurbished percentage. As a result, the LI serves as a complementary indicator that should be used in conjunction with other indicators to address missing criteria and strike the right balance among all criteria, ultimately contributing to a holistic assessment of circularity. The existing LI falls short in its evaluation, as it does not account for the number of times a resource is utilised and neglects several critical aspects of circularity. To address these limitations, Figge et al. [25] proposed an innovative methodology that integrates both longevity and circularity into a comprehensive two-dimensional indicator for a more objective assessment. Their approach involved refining the initial LI, which had mistakenly incorporated the amount of unrecoverable material rather than recoverable material in its calculations. Furthermore, they expanded the calculation method to accommodate various scenarios, including different frequencies of resource return, refurbishment, and recycling, which were previously limited to just two in the initial indicator. The foundation of their circularity metric lies in determining the number of times a resource is reused within a product system. To combine both longevity and circularity metrics into a unified indicator, they devised a matrix identifying four potential ways to combine these two dimensions: short linear, short circular, long linear, and long circular. Despite addressing many of the limitations of the original LI, this combined approach still failed to consider the additional resources required for recycling and refurbishment scenarios. Consequently, it tended to focus on specific phases of a product's lifecycle while overlooking others. This limitation can be overcome by integrating Life Cycle Assessment (LCA) into the methodology.

**Multi-Criteria Decision Analysis (MCDA) Coupling Material Circularity-Based and Life Cycle-Based Indicators**. One such methodology, developed by Niero and Kalbar [40], employs a MCDA model to combine material circularity indicators with life-cycle-based indicators. They apply the Technique for Order by Similarity to Ideal Solution (TOPSIS) method to integrate these two sets of indicators and resolve potential conflicts. For their circularity calculations, Niero and Kalbar utilised two well-established indicators in the field: the Material Reutilisation Score (MRS) from the Cradle-to-Cradle design framework [41] and the MCI [38, 39]. The MRS, in the context of the technical cycle, quantifies a product's recyclability potential; considering two crucial variables: the intrinsic recyclability (IR) of the product, which represents the percentage of the product that can be recycled at least once after its initial use stage, and the percentage of recycled content (RC). The MRS is derived from a weighted average of these two variables, with the first variable receiving twice the weight of the second; resulting in a final value that ranges from 0 to 100. The use of MCDA effectively resolves conflicts that arise when using LCA or circularity indicators individually, allowing for a balanced evaluation that considers trade-offs between circularity and LCA indicators. Since LCA is a burden-based approach, integrating it with circularity value-based approaches helps identify trade-offs that are vital for a successful implementation of CE concepts. One limitation of this model is its relatively narrow consideration of circularity indicators, as it only includes two. However, there is potential to expand it to encompass more circularity indicators and various aspects, including economic considerations at different levels of analysis, such as at the macro level, as applied to buildings.

**Circular Use of Materials**. This indicator measures the proportion of material that is recovered and reintroduced to the economy, thereby reducing the need for extracting primary raw materials in the general use of materials [11, 42]. The circular use rate of materials is calculated as the ratio between the circular use of materials and the overall use of the material [11, 42]. Total material use (M) is determined by the sum of Domestic Material Consumption (DMC) and the amount of circular material use (U), represented as Eq. (12.2), as follows:

$$M = DMC + U \tag{12.2}$$

DMC refers to domestic material consumption as defined in economy-wide material flow accounts. Circular use of materials (U) approximates to the amount of waste recycled in domestic recovery plants, subtracting imported waste intended for recovery and adding exported waste intended for recovery abroad [11, 42].

**Resource Productivity**. Resource productivity is defined as the added-value created relative to the amount of material used and is standardised as the ratio of gross domestic product (GDP) and domestic material consumption. This indicator provides insights into how efficiently materials are used in generating economic output, thereby highlighting the impact of production processes on material consumption [11].

### *12.3.3 Performance Indicators to Measure Construction Material Circularity*

Multiple studies have developed indicators specific to the construction sector, addressing various aspects, characteristics, and uses of construction materials throughout the lifecycle of construction projects. The following text discusses some of the prominent indicators in this context.

**Construction Material Usage Indicators**. There are various material level indicators used to assess the consumption of construction materials in buildings. The consumption of materials indicators should encompass the total lifespan of a building, including project work, maintenance, repairs, and other related activities, relative to the built area. These indicators should be supported by data on the respective national consumption of materials specific to the construction sector [12].

Level(s) is an EU framework that defines core indicators for the sustainability of office and residential buildings, with *Bill of Quantities* (*BoQ*), *materials and lifespans* (Indicator 2.1) being one of sixteen defined indicators within this framework. Under the Level(s) 2.1 indicator, the mass of construction products and materials required for specific parts of the building is estimated and measured, presented as total amounts and according to the material fractions analysed in the Bill of Materials (BoM). This data is typically presented in tonnes and as a percentage of the total mass per material type and building aspect. Optionally, the cost of materials also might be included, adding units of thousand Euros ('000 €) to the materials [43]. While the Level(s) 2.1 indicator mainly focuses on the construction and installation phase of the building life cycle, it is essential to consider other life cycle phases and material lifespans for a comprehensive assessment. In addition, the information produced with material-level evaluation serves as a basis for upper-level indicators in the framework, such as estimating construction waste (CW) using BoM, providing data for LCA or Carbon Footprint (CF) studies, and other related indicators [43].

Some national institutions have developed their own circularity indicators for the buildings, with the amount of construction materials being one such circularity indicator. As an example, the Spain Green Building Council (SpainGBC) has defined an indicator called Consumption of Construction Materials, which measures the total amount (weight) of the construction materials used in a building. This indicator aims to evaluate resource efficiency and is aligned with Level(s) indicator 2.1. It presents the total weight of construction materials used per unit area of the building ((kg, T)/m$^2$), considering the building's entire lifespan, including project work, maintenance, repairs, and other activities.

It is important to note that this indicator does not differentiate between the origin or source of the products, such as virgin or secondary raw materials [12]. When calculating this indicator, it includes the amount of all the construction materials used, including those that become waste during the building's lifetime. However, it does not account for some other relevant aspects during the use life cycle phase. For example, the amount of concrete used for repair works. Data supporting this indicator includes information on national material consumption specific to the construction sector, as well as the building area information from relevant building permit documents [12].

**Construction and Demolition Waste Management Indicators**. Different material-level indicators focus on assessing the generation of CDW. In this context, Level(s) indicator 2.2 *Construction and Demolition waste and materials* aims to facilitate a systemically planned management of CDW, promoting reuse, recycling or recovery of elements, materials and wastes through segregated collection of CDW throughout the lifetime of buildings. This indicator represents a part of the framework's macro-objective 2 of establishing resource-efficient and circular material life cycles. Under the Level(s) 2.2 indicator, the overall quantity of waste generated is estimated and measured, and presented both as a total amount and according to the main types of CDW categorised according to the European List of Waste entities. Data collected is typically presented in kilograms (kg) and can also be expressed as kg per unit area (kg/m$^2$) [44]. Indicator 2.2 can be applied at various stages of the project: during conceptual design stage, the information generated can shape the outline of a Waste Management Plan (WMP); during detailed design and construction stage, estimates of CDW can inform a detailed WMP; and during the *as-built* or *in-use* stage, actual inventory data can be collected using the same approach for performance assessment [44].

Another example of a waste management indicator is CDW dumping, proposed by the SpainGBC. This indicator relates to waste produced, distinguishing between hazardous and non-hazardous waste and corresponding to their respective destinations, such as material recovery, fill operations, incineration, or landfills. It is defined as the unit of mass in relation to the annual built-up area ((kg, T)/m$^2$) [12].

### *12.3.4 Water Consumption Indicators*

Recognising water as one of the most valuable resources for construction and building activities, the methods of obtaining, optimising use, and exploring recovery options for reuse and recycling are critical strategies within the CE framework. Various indicators are employed to assess water consumption in buildings, with the Level(s) indicator 3.1 *Use stage water consumption*, standing out as a notable example. This indicator measures the total water consumption during the use phase of a building, covering water consumed inside and outside of the building. The data is presented as the total amount per average building occupant with the option of analysing amounts of potable and non-potable water in fractions. The collected data is presented in units of cubic metres (m$^3$) per occupant per year. Indicator 3.1 plays a vital role across different stages of building development. During the conceptual design phase, the information gleaned can directly or indirectly affect water consumption, especially potable water, during the use of the building. In the detailed design and construction phase, the influence of various design features and equipment purchases on estimates of water consumption during the use stage can be assessed. Lastly, during the *as-built* and *in-use* stages, fostering awareness and providing information on circular design features and their potential future value is facilitated by this indicator [45].

Another indicator related to water consumption is defined by the SpainGBC [12], encompassing water consumed during both the use phase of buildings and the water used during material production. This indicator presents water consumption presented in cubic metres per occupant per year (m$^3$/occupant/year). Additional indicators related to water include grey water usage, rainwater usage, consumption monitoring systems, water footprint, water consumption per building, reduction in water consumption during the use phase, information systems, water network losses, reuse of nutrients and recovery, system recycling rate, water collection from runoff in the surrounding area of the building, and reduction of water consumption during the EoL phase.

The integration of nature-based solutions (NBS) such as vertical greening systems (VGS)–for example, ground-based green facades, wall-based green facades, pot-based green facades, and vegetated pergola; and green roofs (GR)–including intensive, extensive, semi-intensive, and bio-solar GR, supports water circularity. These systems contribute to water circularity in buildings by promoting water retention and infiltration. However, they also necessitate additional water for irrigation and have embedded water within the structural elements. Rainwater harvesting, source separation, and on-site treatment of wastewater are potential strategies to close the water cycle at building level. Still, a comprehensive analysis is required to assess the necessary additional infrastructure, embedded water, and additional energy demand resulting from water supply, among other factors [46–50].

## 12.4 Environmental and Economic Impact of Construction Materials

This section identifies the allocation of environmental and economic impacts of construction materials and the changes that happen when they are transformed into circular ones. Circularity indicators, under the umbrella of Research, Development and innovation (R + D + i), align with a number of products with EPDs [12]. A comprehensive method for environmental impact evaluation is the LCA. LCA is a powerful, science-based tool for measuring and quantifying the environmental and social impacts of products, services, and business models throughout their life cycle, from raw material extraction to manufacturing, distribution, use, and disposal. LCA has become a significant tool for monitoring the environmental impact of materials used during construction.

Sustainability certifications advocate for LCAs at the building level, ensuring that the impact of construction materials, along with the impact of the building in use, is evaluated globally. Thus, information from materials with an EPD may be incorporated into an inclusive assessment of buildings [12].

### *12.4.1 Carbon Footprint Impact of Construction Materials*

As a petroleum derivative, plastics have a negative environmental impact (refer to Table 12.4) [8]. The production of fibreboards consumes low energy (5 kW-h/$m^3$); however, aluminium and steels have a high energy cost in relation to their extraction and transformation [8]. Restitution of the impact on both GHG emissions and biodiversity is one of the key aspects of the CE principles applied in the construction sector [8]. On a positive note, biochar-filled building materials show great potential in reducing carbon footprint. Biochar, derived from waste biomass, is carbon negative ($-1.88$ kg-$CO_2$-eq/kg carbon footprint) (Table 12.4) [51, 52]. Table 12.4 illustrates

**Table 12.4** Construction materials and their environmental impact (adapted from Ferrer et al. [8])

| Material | Positive | | Environmental impact[a] | | |
|---|---|---|---|---|---|
| | | | Intermediate | Negative | Variable |
| | High | Medium | | | |
| Adobe | ○ | | | | |
| Agglomerated cork | | ○ | | | |
| Alternative plastics | | ○ | | | |
| Aluminium | | | ● | | |
| Cements:<br>Cement–limestone and clay<br>Ecological cements | | ○ | | ● | |
| Concretes:<br>Biological concrete<br>Conventional concrete<br>Conventional reinforced concrete<br>Photocatalytic concrete<br>Recycled concrete | | ○<br>○<br>○ | | ●<br>● | |
| Fibres | | ○ | | | |
| Fired clay | | ○ | | | |
| Paintings | | | | | ◌ |
| Plastics | | | | | ◌ |
| Steels | | ○ | | | |
| Stone | | | ● | | |
| Biochar | ○ | | | | |
| Wood | ○ | | | | |

[a] ○positive (high/medium) environmental impact; ●intermediate environmental impact; ●negative environmental impact; and ◌variable environmental impact

the environmental impact nature of common conventional construction materials, categorised as positive, intermediate, negative, or variable.

**Case Study**. In this case study, adapted from Dsilva et al. [53], the authors employed LCA due to its enormous benefits in facilitating proactive decision-making before construction begins. This section discusses the LCA conducted for two construction scenarios: the business-as-usual scenario and the actual scenario. The results focus on major construction items and their impact within the product stage A1 to A3 (A1—Raw material extract/process/supply, A2—Transport and A3—Manufacture). The functional units in these analyses varied depending on the type of material input, leading to the derivation of information about the amount of embodied carbon generated per square metre of the built-up area (BUA). The main objective of the study was to quantitatively evaluate various measures aimed at reducing embodied carbon, which were implemented by the project team. The study highlights the evidence collected during the construction of the three storey SEE Institute located in The Sustainable City, at the heart of an area called DubaiLand in Dubai, UAE. This multi-storey, multi-purpose structure was designed to accommodate various activities and functions and spans over 4515 m2 of gross floor area. Two specific products were analysed: concrete (*in-situ* and precast) and reinforcement steel. In the business-as-usual scenario, industrial average concrete mixtures were analysed. In contrast, in the actual scenario, concrete mixtures incorporating slag (GGBS) and silica fume (MS) as partial replacements for cement (OPC) were utilised. Additionally, the project team opted for reinforcing bars made of recycled steel. Table 12.5 illustrates the different material types used in each scenario.

The LCA allowed the project team to quantify embodied carbon and implement reduction strategies. A notable advantage of circularity is the carbon savings achieved through recycled materials. Embracing circularity helps reduce emissions even under design and materials choice constraints. Accordingly, Table 12.6 demonstrates the $CO_2$ emission reductions through the use of building materials with increased recycled content in the actual scenario compared to business-as-usual scenario.

This case study on a newly constructed three storey multi-use building demonstrated a substantial reduction in carbon emissions (26%) through proactive material selection and careful sourcing. The study underscores the importance of thoughtful material selection, strategic planning, and consideration of the climatic conditions in choosing construction materials, aiming to promote a CE and mitigate adverse environmental impacts in the construction industry. Implementing the recommendations discussed in this study can empower the construction sector to actively contribute to the transition towards a sustainable and circular built environment.

**Table 12.5** Incorporation of recycled content into each building material for scenarios 1 (industry average–business-as-usual) and 2 (actual–actual scenario)

| Material category | Industry average | Actual |
|---|---|---|
| Ready-mix concrete, C60 | OPC + 10% recycled binders | OPC + GGBS 45% + MS 5% |
| Ready-mix concrete, C50 | OPC + 10% recycled binders | OPC + GGBS 14% |
| Ready-mix concrete, C40 | OPC + 10% recycled binders | OPC + 40% recycled binders |
| Reinforcement steel | 97% recycled steel | 97% recycled steel |

**Table 12.6** $CO_2$ emissions of building materials in scenarios 1 and 2

| Material category | Industry average | Actual | Reduction Per functional unit |
|---|---|---|---|
| Ready-mix concrete, C60 | 442.96 kg $CO_2e/m^3$ | 344.7 kg $CO_2e/m^3$ | 22% |
| Ready-mix concrete, C50 | 390.09 kg $CO_2e/m^3$ | 255.0 kg $CO_2e/m^3$ | 35% |
| Ready-mix concrete, C40 | 355.83 kg $CO_2e/m^3$ | 262.4 kg $CO_2e/m^3$ | 26% |
| Reinforcement steel | 0.62 kg $CO_2e/kg$ | 0.50 kg $CO_2e/kg$ | 19% |

### 12.4.2 *Energy and Indoor/Outdoor Climate Impacts of Construction Materials*

The advancement of circular energy rehabilitation relies on the use of industrialised recyclable materials and energy-efficient technological solutions [8]. Energy consumption associated with a building spans its entire life cycle. From construction through operation to retrofitting and demolition, these phases are crucial considerations during the design phase.

The use phase, which typically lasts 60 to 100 years, necessitates extensive and periodic maintenance to ensure indoor comfort. Numerous LCA studies focusing on buildings have indicated that this phase is responsible for the highest proportion of non-renewable energy use required for achieving comfortable indoor conditions [54, 55].

Table 12.7 illustrates the life cycle phases of a building, emphasising the energy consumption associated with each phase components [56].

The EE typically encompasses energy consumption during the manufacturing and assembly phases of the materials and components. According to Crowther [57], EE is defined as "the total energy required for building creation, including both the direct energy used in the construction and assembly and the indirect energy needed for manufacturing materials and components". However, for authors like Ding [58], EE also extends to the demolition phase.

The assessment of EE involves calculating various phases such as use, maintenance, and demolition, depending on whether a cradle-to-gate or cradle-to-grave boundary definition is used [59].

**Table 12.7** Energies associated with a building during the life cycle phases [56]

| | |
|---|---|
| Construction | |
| Embedded energy | Materials, installations, machines, etc |
| Construction energy | Machines and transport of materials and goods |
| Operation | |
| Climate | Heating, cooling and ventilation |
| Lighting | Lighting of all rooms, halls, corridors |
| Machines, appliances | Computers, fans, washing machine, etc |
| Operating and control | Building management systems |
| Transport | People and goods to and from the building |
| Retrofit | |
| Embedded energy | Materials, installations, machines |
| Construction energy | Machines and transport of materials and goods |
| Demolition | |
| Demolition energy | Machines and transport of materials and goods |

In Khadim et al. [60], a comprehensive review of nano and micro-level building circularity indicators is conducted, focusing on the Integrated Energy Performance and Circularity (IEPC) method as proposed by Sreekumar [61]. This method refers to all systems that consume energy to fulfil functions; such as space and domestic hot water heating, cooling, summer comfort, air movement–*e.g.*, fans, and lighting.

The framework, known as Resources, Reuse/cascades, and Outputs, is translated into quantifiable indicators to assess energy flows and determine the overall circularity degree: IN 1-Energy input (both delivered and on-site generated); IN 2-Material input (pertaining to on-site energy installations) and energy resources; IN 3-Energy reuse; IN 4-Energy output; and IN 5-Material output (related to on-site energy installations).

Reich et al. [62] employed the DPSIR (Driving forces-Pressure-State-Impacts-Responses) analytical framework–originally developed by the European Environment Agency (EEA)–based on an OECD (Organisation for Economic Co-operation and Development) model, to compile suitable indicators.

The construction of buildings necessitates materials produced from raw resources and energy inputs. The excavation of these virgin raw materials imposes environmental pressure, as recorded by pressure indicators P1 (tonnes of virgin raw materials, fuels and water). The response indicator R4, Heating efficiency (kWh/m$^2$), should be recorded to trace policy effectiveness.

It should be noted that measuring EE is not the same as embodied carbon. The focus on reducing embodied carbon is laudable, and great strides are being made within Europe to reduce embodied carbon in energy sources. However, as embodied carbon is reduced, policymakers must not ignore EE, which will remain the same without strides to improve energy efficiency and eliminate energy wastage. The nature of the energy hierarchy requires society to conserve high quality energy if energy equity for all global citizens is to be achieved.

## 12.5 Conclusions and Recommendations

Optimising the use of industrial materials and products is imperative for transitioning industrial systems to a CE. Construction materials serve as the foundational elements of a building, exerting substantial influence on circularity levels within the built environment. The incorporation of innovative circular materials and the application of circularity criteria to traditional materials, notably concrete and steel–widely employed in construction–can profoundly impact the environmental and circular performance of buildings. This impact is realised by advocating for waste hierarchy and resource conservation in response to material scarcity and global environmental challenges.

This chapter identifies overarching circularity criteria in construction materials, delineates diverse strategies to enhance the circularity of traditional materials, and explores novel materials that support a CE in the built environment. Four groups of indicators from the literature are discussed, along with their potential applications to foster a CE in the construction sector. The chapter underscores the role of material circularity in reducing CDW, GHG emissions, and conserving energy, costs, and water resources through multiple strategies aligned with waste hierarchy principles.

Future research endeavours should concentrate on augmenting circular characteristics and criteria at the material level in buildings, particularly when coupled with circular design options. Proper design is crucial, as inadequately designed components and systems hindering material separability and recovery limit the efficacy of circularity even when using circular materials. Circular design ensures seamless material outflows, facilitating waste hierarchy promotion, safe recovery, damage minimisation, and prevention of waste generation.

Furthermore, research could prioritise identifying crucial criteria and characteristics with the potential to enhance circularity values. A multi-criteria model could be developed, ranking materials based on their circularity potential throughout their lifecycle. Exploring circular approaches for utilising conventional construction materials, especially concrete, necessitates further investigation through testing and prototyping. This exploration aims to enhance the circularity of widely used construction materials, addressing the significant environmental footprint of concrete and mitigating current down-cycling activities that contribute to the lower tiers of the waste hierarchy. Fostering circularity for other prominent construction materials beside concrete and steel should also be a focus for future research.

Further research is also needed to establish benchmarks in terms of reuse and recycling among other circularity options for construction materials to achieve maximum circularity values. Additionally, addressing more case studies showcasing the environmental, economic, and social impacts of circular materials applications in buildings is essential.

Lastly, the development of certification programs and dashboards to promote the recognition and visibility of circular materials is worth investigating. This initiative would underscore the enhancement of brand reputation linked to CE initiatives and encourage responsible investments. Similar to green building certification, circular material certification can be integrated into a ranking system that encourages and rewards the use of top-performing circular materials. This approach can attract green financing and promote global collaboration in sustainable and circular construction practices.

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