# Chapter 13
# Circularity Criteria and Indicators at the Building Component and System Level

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**Abstract** The implementation of circular economy principles in building activities holds the potential for substantial environmental, economic, and social benefits. Although extensive research has examined the impact of circularity strategies on various aspects of buildings, there is a significant gap in the literature focusing specifically on building components and systems (BC&S). Most existing studies develop

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indicators applicable to buildings as a whole or solely at the materials level. This study aims to address this gap by identifying and emphasising specific circularity criteria for BC&S, including structure, infill, and services. The primary objective is to elucidate the contribution of each system to the overall circularity of buildings, thereby prioritising the most impactful circularity aspects. At the component level, it is essential to consider the specific attributes of component assemblies that constitute a system. To enhance the practical application of these findings, the study is supplemented with relevant case studies demonstrating best practices for circularity in BC&S. These case studies provide empirical evidence and practical examples of how targeted circularity strategies can improve the sustainability and efficiency of building practices, thereby advancing the goals of the circular economy.

**Keywords** Circular economy · Building components and systems · Circularity criteria · Sustainability · Efficiency · Case studies

## 13.1 Introduction

It is widely acknowledgeable that buildings and their related activities have a significant impact on the environment. The construction industry, in particular, consumes vast amounts of natural resources and raw materials, making it a leading resource-intensive sector [1]. The building sector is accountable for the utilisation of 3 000 million tonnes of natural resources each year [2]. Furthermore, a study conducted by the World Resources Institute indicated that 40% of the worldwide waste generation is attributed to the construction industry [3].

To address these environmental challenges and promote sustainability, the concept of the circular economy (CE) has emerged as a transformative approach aimed at reversing the narrative by creating positive impacts on the environment, economy and society.

Traditionally, the construction industry follows a linear supply chain often characterised by a "take, make, and dispose of" model, involving activities such as mining and extraction, processing and manufacturing, and waste management and disposal. In contrast, the CE seeks to establish a closed-loop system where resources are conserved and brought back into the lifecycle after use [4].

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Buildings are essential components of urban landscapes, shaping their architectural character. However, they are also complex objects comprising intricate systems and numerous components and materials, all interconnected to ensure safety and functionality for occupants.

The previous chapter explored the general circularity criteria for construction materials, highlighting practices for key materials such as concrete and steel. This chapter, however, focusses on the circularity criteria and indicators at two levels of building assembly:

- Component level: Components are the most granular elements of buildings after materials. They can be made of single materials shaped to connect with surrounding components and building parts, or they can be assemblies of multiple materials forming different building components (e.g., windows, doors, roofs, walls, and foundations) [5].
- System level: Systems are assemblies of components and materials serving a specific function [6].

Given the significant potential for implementing CE principles in the building industry, this chapter sheds light on the circularity criteria and indicators for buildings at both the system and component levels. The chapter is structured as follows: Following the introduction in Sects. 13.1 presents a thematic analysis on nine key topics and strategies relevant to circularity in building components and systems (BC&S). Section 13.2 explores the relevance of two prominent circularity models—R-Principles and ReSOLVE—and their applicability to BC&S. Section 13.3 offers an approach to categorising CE criteria for BC&S. Section 13.4 provides examples of best practices for enhancing the circularity of BC&S. Lastly, Sect. 13.5 presents the chapter conclusions, highlighting potential directions for future work and research in this area.

### *13.1.1 Thematic Analysis for Building Components and Systems (BC&S)*

To evaluate the alignment of building components and systems (BC&S) with CE principles, it is essential to explore the circularity aspects applicable to BC&S, particularly in terms of resource efficiency, energy efficiency, and waste reduction throughout the various lifecycle stages. These aspects influence CE principles of closing, slowing, and narrowing material loops through reusing, recycling, and extending the lifespan of buildings and their products and materials.

This section delves into various themes of circularity and its strategies as addressed in the literature on the construction sector, presenting a comprehensive exploration of key elements, with a focus on BC&S. The thematic analysis navigates through diverse topics, starting from the design stage, addressing design for adaptability, disassembly, and durability, through the construction stage, focusing on modularity and standardisation, to the use stage, highlighting the advantages of adaptive building reuse and maintainability for energy-efficient operations. Finally, at the end-of-life (EoL) stage, it explores the principles of reducing, reusing, and recycling BC&S and the need for adopting product responsibility throughout the lifecycle, along with the opportunities for transitioning to circular business models through sharing and exchanging approaches.

By dissecting these themes, readers will gain a holistic understanding of the indicators and criteria shaping the circular construction landscape for BC&S.

### *13.1.2 Design for Adaptability (DfA)*

Adaptability, as described in ISO 20887:2020(E), refers to the capacity to "accommodate changes in use type, demographics, user needs or due to the need for adaptation to external factors, such as climate change, for resilience or futureproofing. The initial cost may be balanced against the future cost of adaptation" ([7], p. 11). In the literature, adaptability is described as the capacity of buildings to change in response to varying needs [8]. These needs arise from various circumstances throughout a building's lifecycle, including social and local factors, environmental changes, emergent technical needs, functional improvements, economic and legislative factors, and differing stakeholder interests [8].

The term "adaptability" has been interpreted in different forms in literature studies, depending on the context [9]. It is widely recognised that Design for Adaptability (DfA) strategies and concepts pertain to BC&S. This relevance is evident in the various interpretations and definitions provided by literature studies. Table 13.1 outlines some of the most common definitions and their relevance to specific BC&S.

However, all the definitions refer to strategies to address different dimensions of change in buildings, which can include changes in size, use or function, performance, configuration or space, location, and changeable components. The concept of adaptability can be alternatively referred to by other terminologies that describe specific strategies or dimensions of adaptability for particular building systems. For example, flexibility often refers to the rearrangement of elements and systems within the infill or building interiors [15]. In this sense, flexibility is considered a part of adaptability, which encompass both internal and external changes.

Other terms used to refer to size adaptability include expandability, extendibility, scalability, and elasticity. Meanwhile, terms such as transformability, changeability, and convertibility refer to spatial changes and reconfiguration of the interior to fit new use or function requirements. Design complexity affects the level of adaptability, and key strategies addressing this aspect are referred to as generality, simplicity, commonality, and open plan. All these strategies share the primary goal of supporting change and ultimately extending the useful life of a building, therefore, they are considered dimensions of adaptability [8].

The importance of designing buildings for adaptability within the context of the CE lies in its potential to slow material loops by extending the service life of buildings

**Table 13.1** Common definitions of adaptability

| Definition | Referred systems/ components | Source |
|---|---|---|
| "A building that has been designed with thought of how it might be easily altered to prolong its life." | All types of systems | [10], p. 8 |
| Structural adaptability is "The capacity of the building structure to be able to undergo changes to the structure itself, with or without only small consequences for the remaining building storeys." | Structure | [11], p. 2 |
| The capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through life | • Space plan<br>• Structural facility systems | [12], p. 3 |
| Adaptable architecture is "an architecture from which specific components can be changed in response to external stimuli, for example, the users or environment." | • Space plan<br>• Structure components | [13], p. 167 |
| "The ease with which buildings can be physically modified, deconstructed, refurbished, reconfigured, repurposed, and/or expanded" | • All types of systems components | [14], p. 2 |
| "The capacity of a building to accommodate change in response to the emerging needs or varying contextual conditions, therefore prolonging its useful life while preserving the value for its users over time." | • All types of systems | [8], p. 11 |

despite inevitable changes over time [8, 16]. This approach is essential for avoiding premature demolition, reducing material waste, and cutting costs, all of which are valuable for a CE by conserving resources and minimising emissions.

Adaptability can be incorporated into building systems to address both unknown future changes or specific anticipated change scenarios. ISO 20887:2020(E) identifies three main dimensions of adaptability: versatility, convertibility, and expandability [7]. These principles represent different levels of change:

1. **Versatility** applies to spatial systems, referring to their ability to accommodate various functions with minor system modifications.
2. **Convertibility** involves making more significant modifications to meet substantial changes in user needs, yet it is related to versatility as both principles involve using single spaces for multiple purposes.
3. **Expandability** involves the addition of extra space horizontally or vertically, significantly impacting the structural system, facade systems, and services needed for the additional space.

DfA involves incorporating specific design features in building systems, enabling them to adapt to emerging needs throughout their lifecycle. This type of adaptability, known as "preconfigured adaptability" [17], entails integrating certain features during the design stage to foster a building's capacity to respond to changes during subsequent lifecycle stages.

However, adaptability can also be applied to buildings not originally designed with adaptability in mind. This can be achieved through adaptive reuse strategies, which involve the "reconfiguration" of systems during the operational stage to prevent a premature EoL [17]. Adaptive reuse, or reconfigured adaptability, is discussed in a later subsection in the thematic analysis.

Historically, the "open building" concept [18] is considered the foundation of the concept of adaptability in building design. The open building approach distinguishes between two types of building systems: support system, which is the structural core, and infill systems, which is the flexible interior subject to user changes. These two systems should be integrated with minimal interface problems to support adaptations by allowing functional independence for each.

The "shearing layers" concept introduced by Brand [19] provides a different categorisation of systems and elements in buildings. The concept is widely recognised in the literature as a key enabler to adaptability [8, 20]. It identifies six layers of building systems and components, as illustrated in Fig. 13.1: site (lasts forever), structure (30 to 300 years), skin (20 to 40 years), space plan (3 to 30 years), services (7 to 20 years), and stuff (approximately ten years). These layers represent categories of building systems according to their timescales, with each layer including components and functions of similar lifespans. By ensuring functional independence for each of these layers and minimising their interactions, a building can adapt and respond to change.

A distinct categorisation of building elements was introduced by Durmisevic and Brouwer [21], who described a three-dimensional transformation: structural, spatial, and material. This transformation is enabled by a certain level of interdependency and exchangeability among components. They emphasised the role of demountable connections as a critical factor in facilitating change between four functional levels in buildings: building, system, component, and materials. Using a top-down approach, a building can be separated into systems, which in turn can be split into components, and further broken down into materials. The role of demountable connections is also

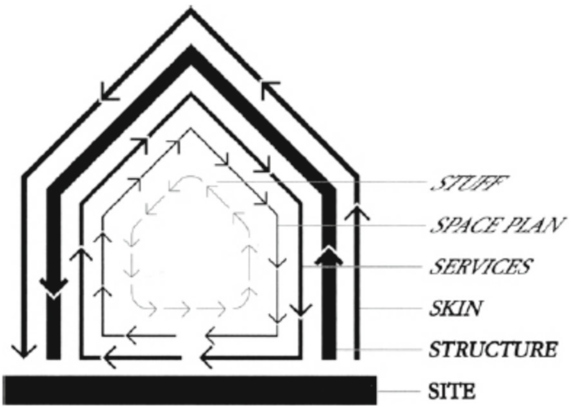


**Fig. 13.1** Brand's shearing layers of change (1994)

emphasised by Design for Disassembly (DfD), which is seen as a supportive strategy for DfA. DfD will be discussed in a subsequent subsection of this chapter.

Multiple frameworks to assess adaptability based on different criteria have been proposed by studies. Table 13.2 addresses these criteria and indicators grouped into Brand's layers, excluding the site and stuff layers. The site is context-related and more relevant to the building as a whole, while stuff is usually the user's responsibility and does not act as part of the building's rigid entity.

Some criteria can pertain to more than one layer and can influence different systems. Therefore, it is important to avoid double-counting these criteria, especially when evaluating the adaptability of layers or systems separately.

The DfA criteria are typically addressed during the concept design phase using a checklist to ensure proper planning. In a more detailed design stage, buildings can be evaluated using a semi-quantitative approach by weighting the criteria based on experts' opinions to prioritise the most impactful adaptability criteria. Alternatively, pre-weighted criteria from existing frameworks like FLEX 4.0 [24], the AdaptSTAR model [22], or the Level(s) framework Indicator 2.3 Design for Adaptability and Renovation [23] can be used.

At the component level, the most important characteristics to enable DfA are standardisation, durability, and reversibility [25]. Standardisation can occur at different levels: material, component, and interfaces and connections [8]. Standardising materials used in assemblies and components provides manageable conditions for more efficient and effective recycling processes. Standardising components or assemblies creates specific conditions for connections and interfaces, allowing design simplicity. Standardising interfaces or connections is regarded as more advantageous for circularity and more efficient to achieve, as it allows interchangeability and exempts components themselves from being standardised while providing efficiency for material disassembly [8].

Component durability can be defined by the length of product use life and the intensity of use, addressing multiple use cycles. Component durability is also related to the conditions of the system to which it belongs, making it important to address accessibility for repair and replacement. More details are explained in the following subsection on Design for Durability.

Lastly, component reversibility, which allows for the safe recovery of components or their composing materials with minimal damage, is defined by the types of interfaces and connections, as well as accessibility for replacement and recovery. However, reversibility criterion significantly overlaps with DfD concepts and will be further addressed in DfD subsection.

### *13.1.3 Design for Durability*

Design for durability involves considerations of expected lifespan, intensive use, maintenance requirements, and resistance to wear and tear. These parameters are crucial in industrial construction methodologies to ensure slower material loops by

**Table 13.2** Classification of existing adaptability criteria and indicators for building systems (non-exhaustive list)

| System | Criteria | Framework and source |
|---|---|---|
| Structure | Structural Integrity-structural design of the building to cater to future uses and loads | AdaptSTAR [22]<br>Level(s) [23] |
| | Positioning of columns/design complexity | AdaptSTAR [22]<br>FLEX 4.0 [24]<br>Level(s) [23] |
| | Greater ceiling heights for surface routes | FLEX 4.0 [24]<br>Level(s) [23] |
| | Structural durability | AdaptSTAR [22] |
| | Surplus of building space/floor space | FLEX 4.0 [24] |
| Skin | Façade windows to be opened | FLEX 4.0 [24] |
| | Day light facilities | |
| | Non-load bearing facades | Level(s) [23] |
| | Façade pattern | |
| Space plan | Flexibility/multifunctional building | AdaptSTAR [22]<br>FLEX 4.0 [24] |
| | Access to building: horizontal routing, corridors, gallery | |
| | Disassembly/disconnecting, removable, relocatable units in building | |
| | Disassembly/disconnecting, removable, relocatable interior walls | |
| | Disassembly/disconnecting/detailed connection interior walls | |
| | Column grid spans/structural grid | AdaptSTAR [22]<br>Level(s) [23] |
| | Compartmentalisation/internal wall system | |
| | Compartmentalisation/the potential for segregated home working spaces | |
| | Compartmentalisation/the potential for ground floor conversion to a contained unit | |
| | Possibility of suspended ceilings | FLEX 4.0 [24] |
| | Possibility of raised floors | |
| | Distinction between support and infill | |
| | Unit size and access | Level(s) [23] |
| Services | Ease of access to service ducts and building services | AdaptSTAR [22]<br>Level(s) [23] |
| | Ease of access to plant rooms | Level(s) [23] |
| | Longitudinal ducts for service touts | |
| | Higher ceilings for service routes | |
| | Services to sub-divisions | |
| | Ease of adaptation of the distribution networks and connectors | |

allowing intensive and prolonged use of BC&S, thus postponing their EoL phase. Durability should be prioritised for structural systems, which must be robust enough to handle various load scenarios, facilitating future adaptations [20]. In this sense, durability is essential for adaptability, which requires structures strong enough to meet performance requirements for changes in use, function and size [8].

Durability is also important for other systems, such as façade and interior systems, to ensure they are used to their fullest extent, thereby reducing material inputs. This not only extends the service life of these systems but also minimises the need for frequent replacements and repairs, leading to lower resource consumption and waste generation. Additionally, durable façade and interior systems contribute to the overall energy efficiency and performance of the building, further supporting sustainability goals. By focusing on durability across all building systems, the long-term environmental impact and operational costs can be significantly reduced.

At the component level, durability depends on the duration and intensity of use, defined by the service life and the number of cycles the component or product undergoes, respectively. According to the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation and Granta Design [26], components that last longer than their industry average equivalents contribute to greater circularity. This is related to component quality and the conditions of materials constituting the component. A component's service life is determined by the shortest lifespan among its materials; ideally, these materials should have similar lifespans. If one material deteriorates while the rest remain functional, the component reaches its EoL. In this sense, DfD becomes a key complementary strategy for durability, ensuring that components can be dismantled and their materials recovered for reuse or recycling.

Furthermore, durability is relevant to the accessibility of components for replacement and maintenance. Thus, durability is again associated with DfD and easy maintenance strategies, which provide criteria for the accessibility of elements and their demountability without causing damage to them or adjacent elements.

### *13.1.4 Design for Disassembly (DfD)*

DfA encompasses several circularity strategies and associated concepts, such as flexibility, convertibility, and expandability [27], which have a significant impact at the building system level. At the component level, DfA principles are closely associated with Design for Disassembly (DfD). However, DfD is also relevant at system level, particularly impacting shorter-life systems like services, and often overlaps with multiple DfA strategies.

The close association between DfA and DfD is reflected in the fact that multiple aspects of these two concepts are often approached under the same umbrella. For example, well-known methods for assessing adaptability often consider DfD-related issues, as seen in studies by Geraedts [24] and Conejos et al. [22]. In some cases, these concepts are treated in a unified context (e.g., [28]). Table 13.3 presents DfD criteria considered in DfA models, namely AdaptSTAR by Conejos et al. [22], and

**Table 13.3** Indicators related to disassembly in FLEX 4.0 and AdaptSTAR

| Tool/method | Indicator/criterion for DfD |
|---|---|
| FLEX 4.0 [24] | Dismountable facade |
| | Modularity of facilities |
| | Disconnection of facility components |
| | Accessibility of facility components |
| | Disconnectable, removable, relocatable building units |
| | Disconnectable, removable, relocatable interior walls |
| | Disconnecting/detailed connection interior walls; hor/vert |
| AdaptSTAR [22] | Disassembly-options for reuse, recycling, demountable systems, and modularity |

FLEX 4.0 by Geraedts [24]. The criteria/indicators listed are those directly referring to the strategies of disconnection and disassembly.

DfD is a structural component of DfA since it facilitates the adaptation of BC&S in various contexts. For example, the potential for reconfiguration of building elements (e.g., to meet differentiated requirements of performance) and their rearrangement (e.g., due to changes in fit-out construction) heavily depends on the feasibility and manageability of disassembling the building elements. This also applies to the potential for repair, upgrade or substitution of electro-mechanical equipment, and the removal of components or systems at the end of their service life or when the building needs to adapt to new conditions.

Although DfA and DfD are evidently related, still they are identified as distinct strategies [27, 29]. DfD is defined in various ways in the literature, with an indicative list of definitions presented in Table 13.4. According to ISO 20887:2020 ([7], p. 3), DfD is defined as "An approach to the design of a product or constructed asset that facilitates disassembly at the end of its useful life, in such a way that enables components and parts to be reused, recycled, recovered for energy or, in some other way, diverted from the waste stream," with the term "disassembly" standing for "non-destructive taking-apart of a construction work or constructed asset into constituent materials or components."

The concept of DfD is frequently mentioned or used interchangeably with "Design for Deconstruction" in the literature [31, 33, 34], although there are important distinctions between the two concepts. O'Grady et al. [35] point out that disassembly relates specifically to the EoL stage of a building, involving the careful dismantling of its elements, parts, or components for reuse. In contrast, deconstruction primarily refers to the removal of a building's structural elements with the potential for reconstruction, such as relocating the building. The contribution of DfD processes in the building sector towards the implementation of CE principles is well established. DfD facilitates maintenance, repair, and substitution of BC&S, enhances adaptability, prolongs the service life of units integrating constituents with shorter lifespans, limits resource consumption via the reuse of materials or components, and reduces waste and environmental impact.

**Table 13.4** Indicative (not exhaustive) list of definitions for DfD appearing in the literature

| Definition | Source |
|---|---|
| "The concept of designing buildings in such a way to facilitate future dismantling, thereby reducing the generation of waste by guaranteeing the possibility of all circular building product levels to undergo re-life options (service, reconfiguration, redistribution, remanufacture, recycling, cascaded use, and biosphere) in a hierarchical way, achieved by the implementation of disassembly determining factors in building design." | [30], p. 257 |
| "A method to design a building/product to enable the disassembly of building/ components and reuse/recycling of its parts. The components need to be assembled in a sequence planning suitable for maintenance and reconfiguration of their variable parts." | [31], p. 572 |
| "Design which facilitates construction to be reversible, and dismantled connections and elements to be reusable following the conclusion of the design life for potential use in another building." | [32], p. 2 |

The strong interconnection between DfD-related issues and circularity implementation is demonstrated by the inclusion of DfD in several CE-related schemes, assessments and monitoring frameworks. DfD can be envisioned at various scales within a single building, including the material, component, system, and the whole-building levels. Ensuring the feasible and easy disassembly of building components involves addressing issues related to the materials constituting the components. Similarly, disassembly at the system level depends on the conditions of individual components, and the disassembly of the entire building relates to the configuration and characteristics of its composing systems. This multi-level nature of DfD is reflected in approaches that consider human factors [GP1] [36]. Realistic solutions must address not only the technical aspects of DfD (e.g., type of connections) but also human factors, such as accessibility and ease of disassembly. Given the interdependencies among these different scales, DfD should be based on a holistic view of the design product, considering the EoL of an entity and its constituent parts. This approach must account for the different service life durations and or expectancies of BC&S.

Brand's layering system [19] is frequently applied to address the varying lifespans of building parts [32, 34, 36]. Longevity and durability are critical considerations, as exposure to various deterioration mechanisms affects components and systems differently. It is worth noting that identifying the end of service life involves not only technical but also economic and functional criteria [37].

Table 13.5 presents a list of indicators and criteria for DfD, as encountered in various tools and bibliographic sources. The list is not exhaustive and does not represent all existing approaches in the literature. The emphasis is on criteria addressing the BC&S levels, with reference to the building level when relevant.

In the first model discussed in Table 13.5 [38], the criteria are categorised into eight major groups, as shown in the table's final column. These criteria are further analysed in Durmisevic's study [38] in relation to the performance levels corresponding to the benchmarks of the assessment score scale. Moreover, these factors served as the foundation for the Building Circularity Indicator (BCI) [40]. This indicator has since

**Table 13.5** Non-exhaustive list of indicators/criteria in design for disassembly/disassembly potential assessment models

| Source | Indicator/criterion for DfD | Notes |
|---|---|---|
| [38] | Functional separation | Category: functional decomposition |
| | Functional dependence | |
| | Structure of material levels | Category: systematisation |
| | Type of clustering | |
| | Base element specification | Category: base elements |
| | Use life cycle coordination | Category: lifecycle coordination |
| | Technical life cycle coordination | |
| | The lifecycle of components and elements in relation to the size | |
| | Type of relational pattern | Category: relational pattern |
| | Assembly direction | Category: assembly |
| | Assembly sequences | |
| | Geometry of product edge | Category: geometry |
| | Standardisation of product edge | |
| | Type of connection | Category: connections |
| | Accessibility to fixings and intermediary | |
| | Tolerance | |
| | Morphology of joints | |
| [39] | Connections types | Used in the model for the derivation of the disassembly potential of the connection |
| | Connection accessibility | |
| | Interdependency | Used in the model for the derivation of the disassembly potential of the composition |
| | Geometry of product edge | |

provided the basis for modified building circularity metrics, as documented in [6]. For example, van Vliet [39] expanded upon the potential for measuring disassembly.

The second approach outlined in Table 13.5 [39] evaluates the disassembly potential of each product or element based on two key factors: (i) the disassembly potential of the connection (derived from the first two indicators/criteria listed in the table, as indicated in the final column) and (ii) the disassembly potential of the composition (derived from the last two indicators/criteria listed in the table, as indicated in the final column). At the building scale, the overall disassembly potential is determined by the respective potential of each "layer" comprising these elements.

### 13.1.5 Modular Construction and Prefabrication

Using prefabricated and modular BC&S is a strategic approach to promoting circularity in buildings. These components, produced in a factory setting, can be easily assembled and disassembled, facilitating the recovery of materials for reuse and recycling. Modular construction is recognised as one of the Modern Methods of Construction (MMC). The definition of MMC varies globally, reflecting regional preferences and terminologies. In Asia, terms such as "off-site manufacturing," "prefabrication," and "industrialised building systems" are commonly used. In contrast, the United Kingdom refers to "MMC" as next-generation construction methods. In the United States and Australia, the terms "off-site construction methods" and "modular construction" are predominantly used.

Modular construction (MC) can be classified into two distinct categories: on-site MC and off-site MC. On-site MC combines conventional or sustainable materials with advanced production techniques like digital building modelling (e.g., Digital Twin (DT) and additive manufacturing.) This involves the direct production and assembly of components and systems at the construction site. In contrast, off-site MC utilises preassembled panels or modular units fabricated within a controlled industrial environment. These components are then transported to the construction site for assembly [36, 41, 42]. Both on-site and off-site MC enhance construction efficiency by streamlining the production and assembly processes.

MMC, synonymous with MC, involves the use of factory-produced BC&S in construction [43]. Factory-based manufacturing processes improve construction efficiency during both the manufacturing phase and the subsequent on-site integration phase. MMC encompasses a wide range of technologies, including prefabrication, additive manufacturing, Building Information Modelling (BIM), Digital Twin (DT), and Augmented Reality. These technologies, often leveraging innovative sustainable construction materials, streamline the preparation and execution of construction projects. They enhance production volumes, improve quality, and decrease procurement time, significantly benefiting the construction industry [44].

Moreover, MMC implements circular business models (CBMs) that encourage sharing, leasing, and allocating BC&S to generate remuneration from underutilised resources. This approach also increases the percentage of materials circularity (PMC) by reducing carbon emissions and construction waste, and conserving natural resources. One of the principles followed by MMC is Life Cycle Assessment (LCA) [45]. LCA helps identify the most environmentally friendly materials for construction by comparing various structural designs on their environmental performance and circularity potentials. LCA is key for addressing the Global Warming Potential (GWP), Cumulative Energy Demand (CED), and reduction of material waste.

One of the most popular methodologies of LCA is the *"Cradle to Grave"* method, which is illustrated in Fig. 13.2. This methodology is commonly implemented in

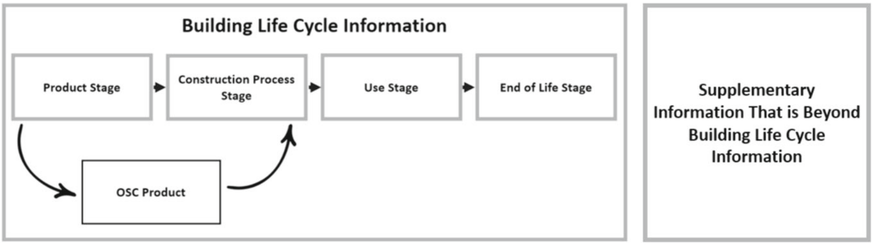


**Fig. 13.2** Cradle to grave–LCA model (adapted from [46], OSC stands for off-site construction)

construction and is integral to MMC. By adhering to the cradle-to-grave methodology of LCA, stakeholders involved in construction can make well-informed decisions aimed at minimising the environmental impact of their projects and fostering sustainability.

In addition, BIM can play a significant role in circular construction by facilitating Building Circularity Assessment (BCA) in the early design stages of a building. Through BCA, parameters and indicators such as material flows, waste generation, and resource efficiency can be identified, aiding in the implementation of circularity in the proposed building. This integration of BIM and BCA ensures that sustainability is embedded from the outset, promoting a holistic approach to circular construction.

### *13.1.6 Adaptive Reuse*

Recent studies emphasise the significant environmental benefits of adaptive reuse of existing buildings [47, 48]. Although these benefits are not yet widely adopted in real-world scenarios, research on specific buildings has shown substantial reductions in energy consumption, carbon dioxide, and other greenhouse gas (GHG) emissions, as well as decreased use of fossil fuels, fresh water, and materials [49].

Adaptive reuse retains the building but alters its usage to meet new needs, thereby avoiding demolition. Historic buildings can be repurposed while preserving their original features, such as facades, decorative elements, or structural systems. Cultural building heritage in cities is particularly noteworthy due to its potential underuse and desertion, despite its valuable historical and cultural significance. These buildings often serve as the keystones of unique urban neighbourhoods worldwide. Adaptive reuse allows for the preservation of historically or culturally significant buildings, maintaining their architectural integrity, contributing to the distinctive townscape and cultural heritage of a place. Buildings may be significant for their design and construction quality or for the ambience they bring to a space. When forming a design team, it is essential to consider that well-preserved buildings can be protected and used in the future.

Adaptive reuse reduces the environmental impact associated with new construction, such as the consumption of raw materials, energy, and waste generation. By reusing existing structures, the embodied energy and resources invested in their construction are conserved, resulting in lower carbon emissions and reduced landfill waste. The interior layout and spatial configuration are modified to suit the new function while respecting existing structural constraints and features. With this regards, open plan schemas can be beneficial in fulfilling future needs.

However, a thorough structural analysis is necessary to assess the building's condition and evaluate its suitability for the proposed new use. Structural retrofitting may be required to reinforce or upgrade the building's structural system, ensuring compliance with current safety standards and building codes. The building's infrastructure and service systems, such as electrical, plumbing, and HVAC may also need to be upgraded or retrofitted to meet the requirements of the new use and improve energy efficiency. In this context, encouraging stakeholder engagement is essential to support adaptive reuse projects, which can be achieved through financial incentives, tax credits, or grants.

When considering functional modifications, adaptive reuse encompasses diverse possibilities, spanning residential to non-residential applications. Converting properties into non-residential public-use facilities, such as museums, libraries, and similar entities, has been acknowledged as a sustainable approach to urban redevelopment, particularly within a cultural setting. This approach not only prolongs the lifespan of the building, reduces waste, and promotes energy reuse but also offers significant economic and sociocultural benefits to the community. These benefits include safeguarding the essence and historical significance of specific periods, preserving the city's identity, rich heritage, and cultural aspects, and upholding community values for both current and future generations, whether they are permanent residents or temporary visitors [50]. Table 13.6 summarises considerations and benefits of implementing adaptive reuse strategies, supporting the principles of CE in BC&S.

In adaptive reuse cases, it is crucial to analyse the existing building's original design and conditions to appraise the most suitable strategies for adaptation based on emerging requirements and circumstances. Multiple frameworks have been developed to assess buildings' suitability for adaptation and support stakeholder decision-making based on multiple dimensions of their conditions and factors influencing their use, including functional, cultural, environmental, economic, social, political and regulatory factors. Examples of such assessment models include the adaptive reuse potential (ARP) model [51], IconCUR [52], and the preliminary assessment adaptation model (PAAM) [53].

### *13.1.7 Easy Maintenance (Maintainability)*

Easy maintenance refers to systems or products that require minimal care or upkeep to maintain proper functionality over long periods. In the context of the CE, easy maintenance strategies involve designing products for longevity, using components and materials that can be reused, and ensuring they can be easily disassembled for repair, refurbishment, or recycling [54].

**Table 13.6** Key benefits and considerations of adaptive reuse in buildings

| | |
|---|---|
| Environmental benefits | Reducing overall lifecycle energy consumption |
| | Conserving embodied energy and resources |
| | Lowering carbon dioxide and greenhouse gas emissions |
| | Decreasing fossil fuel consumption |
| | Reducing freshwater consumption |
| | Optimising materials use |
| | Minimising landfill waste |
| Historic and cultural significance | Maintaining architectural integrity |
| | Contributing to the cultural heritage of a place |
| | Preserving unique historical and cultural characteristics |
| | Highlighting urban cultural heritage buildings |
| Structural safety assessment | Retrofitting structure to meet safety standards and building codes |
| | Ensuring compliance with current safety standards |
| Infrastructure and system upgrades | Upgrading electrical, plumbing, heating, ventilation, and air conditioning (HVAC) systems |
| | Enhancing energy efficiency |
| Financial incentives | Supporting financial incentives |
| | Providing tax credits |
| | Facilitating grants |

Implementing easy maintenance strategies enables businesses and individuals to extend the lifespan and performance of physical assets, prevent breakdowns, reduce downtime, and avoid costly repairs or replacements [55, 56]. Additionally, these strategies optimise energy efficiency and resource consumption of their equipment, which reduces their environmental footprint and operational expenses. These benefits of easy maintenance make it a compelling strategy for incorporating CE into buildings, their systems and components. Table 13.7 outlines various concepts and strategies that call for easy maintenance or maintainability for improved closing and slowing material loops.

To effectively implement easy maintenance strategies in the CE, businesses and individuals can take several actionable steps depending on each case conditions [57]. Table 13.7 outlines some of the actions to facilitate the implementation of these strategies.

Designing buildings with easy maintenance in mind, such as incorporating modular components and accessible infrastructure, can simplify repairs and upgrades, thereby extending the lifespan of the building and its components. Moreover, adopting preventive and predictive maintenance approaches allows building owners and facility managers to proactively identify and address issues before they escalate into major problems. Regular maintenance inspections and servicing ensure

**Table 13.7** Actions for implementing easy maintenance strategies (adapted from [57–59])

| | |
|---|---|
| Maintenance programme | Regularly maintaining products to extend their lifespan and reduce the need for replacement |
| Accessibility | Ensuring all components are easily accessible for inspection, maintenance, and repair |
| Designing products for durability | Creating products that are made to last, with component parts or materials that can be reused |
| Ease of disassembly | Designing products that can be easily disassembled for repair, refurbishment, or recycling |
| Choosing reusable products | Selecting products that can be reused for their original purpose without significant alteration |
| Repairing products | Fixing products when they break down instead of replacing them |
| Recycling products | Separating products into their component parts and recycling them |
| Composting organic waste | Breaking down organic waste into nutrient-rich soil that can be used to grow new plants |
| Condition-based maintenance | Monitoring the condition of equipment in real-time to prevent breakdowns and optimise performance |
| Predictive maintenance | Using data and analytics to predict when equipment will need maintenance, allowing for proactive interventions |
| Remote monitoring | Using sensors and other technology to monitor equipment remotely, allowing for early detection of issues and proactive maintenance |

optimal performance and reduce the likelihood of premature replacements, thereby conserving resources and minimising waste [59].

Additionally, embracing the CE in building maintenance can contribute to a more sustainable materials and waste management system. Proper waste segregation, recycling programmes, and the promotion of repair and refurbishment services can divert materials from landfills and reduce the demand for virgin resources. Furthermore, incorporating energy-efficient technologies and renewable energy systems into building maintenance practices can significantly reduce the environmental footprint of buildings.

### *13.1.8 Component Recovery for Reuse and Recycling*

DfA and DfD are important enablers of a CE in BC&S. Although these strategies are implemented at the design stage, the full realisation of their value happens at the EoL stage when components are recovered. Component recovery, enabled by DfA and DfD, is essential for closing the loop by creating potential for reuse, refurbishment, remanufacturing and recycling. However, the real value is leveraged when established methods for these reuse and recovery pathways are in place. This relies on regional and national factors, including prevailing techniques and materials, market conditions, stakeholder embracing, skilled labour, supporting regulations, and existing standards indicating recycling and reuse rates.

The selection of materials from the planning phase through the design and procurement phases significantly influences their reusability and recyclability at the EoL stage. Here are key strategies to enhance component recovery for reuse and recycling:

1. **Material Selection**: Choose materials that are durable, recyclable, and reusable from the outset. This ensures that at the EoL stage, materials can be efficiently recovered and repurposed.
2. **Establishing Recovery Pathways**: Develop clear and efficient methods for recovering building components at the EoL stage. This includes setting up systems for sorting, transporting, and processing materials.
3. **Lifecycle Management**: Implement Life Cycle Assessment (LCA) to evaluate the environmental impact of building materials throughout their lifecycle. This helps identify opportunities for reuse and recycling, ensuring that materials are utilised to their fullest potential [60, 61].
4. **Collaborative Networks**: Foster collaboration among stakeholders, including architects, engineers, contractors, and waste management companies. This collaboration can lead to innovative approaches and technologies that improve recovery processes and material reuse.
5. **Regulatory Support**: Advocate for policies and regulations that support the recovery and reuse of building components. This includes incentives for using recycled materials and penalties for improper disposal.
6. **Market Conditions**: Understand and adapt to market conditions that affect the viability of reused and recycled materials. This includes creating demand for such materials and ensuring their competitiveness in the market.
7. **Stakeholder Engagement**: Engage all stakeholders in the value chain to embrace CE practices. This includes training and educating skilled labour to handle recovery processes effectively.

### *13.1.9 Product Responsibility*

Circularity practices for buildings aim to reduce environmental impact and resource consumption through strategies that consider the entire lifecycle of a building. Product responsibility plays a key role in addressing the environmental and social challenges associated with the building lifecycle, focusing on the ethical and practical aspects of the materials, components and products used in construction.

Responsible sourcing of materials is crucial, emphasising sustainability from the design phase onward. Factors such as recyclability and reusability should be integrated into Product Service Systems (PSS) to minimise environmental pollution. PSS is an innovative business model that encompasses the design, installation,

**Table 13.8** Key elements of product responsibility to enhance CE in buildings

| | |
|---|---|
| Responsible sourcing | Ensuring that materials are sustainably sourced, recyclable, renewable, and have a low carbon footprint |
| Lifecycle assessment | Evaluating the environmental impacts of materials and components from production to disposal, supporting informed decisions for long-term sustainability |
| Recyclability and reusability | Designing components for easy disassembly, reuse, or recycling at the end of their service life, reducing waste and promoting resource efficiency |
| Innovative business models | Adopting PSS to focus on providing sustainable services covering design, installation, maintenance, and deconstruction |
| Stakeholder collaboration | Engaging suppliers, contractors, and clients to ensure sustainable practices throughout the construction process |
| Regulatory compliance | Adhering to environmental regulations and standards that promote sustainable construction practices and the use of eco-friendly materials |

maintenance, and deconstruction of building materials and components, providing sustainable and efficient solutions throughout the building's lifecycle.

An exemplary application of PSS is seen in the Moringa Company of Germany, whose project in Hamburg HafenCity aims to construct a sustainable building using numerous recycled materials without any pollutants [42]. Table 13.8 outlines key elements of product responsibility for circularity in buildings.

### *13.1.10 Sharing and Exchange Opportunities*

One of the primary objectives of implementing circularity in the construction sector is to achieve maximum efficiency and optimise common processes by moving away from the traditional produce-use-dispose engineering model. The closed-loop system of the CE can be enhanced by integrating and developing a culture of Sharing and Exchange (S&E), as proposed by the ReSOLVE framework [62], among construction industry stakeholders. By sharing common machinery, equipment, databases, software, and by-products from various processes, or by exchanging outdated technologies with innovative ones, the construction sector can align with CE principles [63].

However, several challenges are associated with implementing S&E opportunities in the building sector. An important example is the disjointed supply chain and inefficient information exchange between big players [64]. The resolution lies in adopting new technologies such as Big Data Analysis (BDA), Blockchain technology (BTC), and Digital Platforms, which allow designers to investigate reusable materials and collaborate more effectively [64]. While the implementation of these technologies can be costly, posing a barrier for smaller companies, leading firms like Arup are setting as example by advancing the construction industry towards these new methods, optimised by statements like "from bin to BIM" [65].

Sharing assets like office spaces and public facilities, also known as the collaborative economy or pooling of goods, is gaining popularity in the construction industry. A noteworthy example is the South Australian Government's promotion of collaborative use, management, and maintenance of facilities with similar inputs and outputs, aiming to extract more value while reducing resource flow and consumption [64].

Enhancing the exchange of equipment and materials is crucial for the construction sector. Guidance for transitioning from outdated approaches to contemporary practices can be drawn from the Industrial Symbiosis model, where large companies share services commonly used by everyone [66]. Similarly, construction companies can benefit from sharing machinery or equipment instead of purchasing. Equipment sharing between contractors can be advantageous in terms of finances, time, and convenience, while purchasing or renting equipment in emergencies or shortage can delay work due to additional bureaucracy, transportation, and installation [67, 68]. Practical centralised and decentralised resource-sharing and exchange models, considering allocation and conflict-resolution models, demonstrate the construction sector's progress in implementing CE concepts [68]. Table 13.9 highlights various indicators and criteria for evaluating the implementation of CE in this context.

**Table 13.9** Indicators and criteria for evaluating the implementation of the circular economy in sharing and exchange opportunities in building components and services

| | |
|---|---|
| Efficiency and optimisation | Moving away from the traditional "produce-use-dispose" model towards circularity |
| Sharing and exchange culture | Sharing common resources such as machinery, equipment, databases, software, and by-products, as well as exchanging outdated technologies with innovative ones |
| Resolution of challenges | Adoption of technologies like big data analysis (BDA), Blockchain technology (BTC), and digital platforms to resolve inefficiencies and improve collaboration |
| Collaborative economy | The trend of sharing assets like office spaces and public facilities in the construction industry, also known as a collaborative economy or pooling of goods |
| Resource efficiency | Extracting more value while reducing resource flow and consumption, a key criterion for CE implementation |
| Equipment and material exchange | Shifting from traditional purchasing or renting approaches to more collaborative sharing models |
| Industrial symbiosis | Following the Industrial symbiosis model, where large companies share services, as a direction for transitioning from outdated to contemporary practices in the construction sector |

## 13.2 Circular Economy for Building Components and Systems: R-approaches and ReSOLVE Framework

The principles of the CE are extensively discussed in the literature, evolving from the basic 3R (reduce, reuse, recycle) framework to the more comprehensive 9R framework (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, recover) [69, 70]. The core idea behind R-approaches is to establish a waste hierarchy that prioritises the most effective strategies for minimising resource consumption and waste production, with EoL recycling as the last circular resort.

The 3R principles can be applied to define, apprise and prioritise indicators of circularity for BC&S. The "Reduce" approach involves optimising the number of connections, structural elements, layers, facades components and finishing materials, as well as selecting materials that are lightweight yet durable and maintainable. The "Reuse" approach focuses on preserving the quality of building components from existing buildings for use in new constructions, employing circular practices such as dry methods of structural connections. The "Recycle" approach, as a last resort, involves extracting valuable resources from waste for further use. Recycling can be further categorised into three levels, ranked from most to least preferable: upcycling (e.g. creating new wooden furniture from old wooden boards), recycling (e.g. crushing demolished concrete for use as aggregate in new concrete), and downcycling (e.g., using concrete beams for aggregates for road pavement) [71, 72].

The ReSOLVE framework outlines key actions for transitioning from linear to circular business models: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange [63]. Each of these actions can relate to the circularity of BC&S, guiding the decision-making process. "Regenerate" suggests selecting materials that can be replenished naturally. "Share" advocates for business models that encourage collaborative use of materials, components, equipment, and technology, thus minimising the need for new resources. "Optimise" involves reducing the number of building components and choosing durable elements that require less maintenance. "Loop" aims to minimise waste through reuse and recycling, applying to both the recovery of construction and demolition waste (C&DW) at the EoL stage and the design stage, which should consider disassembly and adaptability techniques to facilitate recycling/upcycling practices without extensive sorting. "Virtualise" involves creating virtual databases to collect data on building materials and components, content, history, and labelling, improving reuse opportunities and reducing waste generation. "Exchange" promotes the development of reclaimed materials markets, connecting value chain stakeholders through providing platforms for sharing, selling or purchasing secondary construction components.

While the R-approaches and the ReSOLVE framework provide valuable guidelines for CE business models, other supporting factors are essential, including a robust regulatory framework, financial incentives, stakeholder interest, and involvement.

## 13.3 Classification of Circularity Criteria and Indicators for Building Components and Systems (BC&S)

In general, the circularity criteria for BC&S can be grouped into the following categories: characteristics of a building component or system, construction and demolition waste (C&DW) management, connections conditions, regulations and documentation and stakeholder involvement. These categories were derived from a comprehensive thematic analysis, which also highlighted additional aspects such as material reuse potential, lifecycle assessment, and economic feasibility. Including these aspects provides a more holistic approach to evaluating circularity in building components and systems. These criteria categories are connected to multiple indicators of the EU monitoring framework of CE by Eurostat [73]. This framework encompasses five distinct thematic areas (TA): production and consumption (TA1), waste handling (TA2), secondary raw materials (TA3), competitiveness and innovation (TA4), and global sustainability and resilience (TA5). Table 13.10 provides information on CE criteria and indicators for BC&S circularity criteria categories and corresponding Eurostat indicators.

### *13.3.1 The Characteristics of Building Components and Systems*

These include the following indicators: maintainability (meaning they can continue to be kept in use through maintenance) and durability [69]. It is also important to consider the recyclability or reusability of the recycled materials to ensure they can continue contributing to the CE beyond their current application. Talking about the interaction with other objects in the structure, systems, and components should be reversible, simple, and fast for connection [74]. From Eurostat circular criteria, the following indicators can be related to BC&S:

- Circular Material Use Rate (can be used to evaluate the circularity level of BC&S materials);
- Contribution of Recycled Materials to Raw Materials Demand
- End-of-Life Recycling Input Rates (EOL-RIR) (this indicator can be used to evaluate the number of recycled materials used in BC&S)
- Trade in Recyclable Raw Materials (this indicator can be used to assess reuse of materials used for BC&S)
- Material Footprint (this indicator can be related to the total amount of building materials and structural elements used during construction and maintenance life stages of a structure)
- Greenhouse Gas Emissions from Production Activities (this indicator relates to the production of BC&S causing GHG emissions, which requires optimised production of BC&S, as well as reuse, sharing, and recycling)

**Table 13.10** A summary of circularity criteria for buildings at component and system levels

| Circularity criteria for BC&S | | | Related indicators from eurostat monitoring framework |
|---|---|---|---|
| Category | Criteria | Source | |
| Characteristics (TA1, TA3, TA4) | Maintainability of the components<br>Durability of the components | [69] | Circular material use rate (cei_srm030)<br>Contribution of recycled materials to raw materials demand-end-of-liferecycling input rates (EOL-RIR) (cei_srm010)<br>Trade in recyclable raw materials (cei_srm020)<br>Material footprint (cei_pc020)<br>Greenhouse gas emissions from production activities (cei_gsr011)<br>Material import dependency (cei_gsr030)<br>EU self-sufficiency for raw materials (cei_gsr020) |
| | Reuse, recycling, and upcycling potential interface: reversibility, simplicity, speed | [74] | |
| Construction and demolition waste (C&DW) management (TA2, TA3) | Total amount of C&DW produced<br>Reuse rate<br>Recovery rate<br>Recycling rate<br>Separate collection rate<br>Reused products from C&DW | [75] | Waste generation per capita (cei_pc034)<br>Generation of waste excluding major mineral wastes per GDP unit (cei_pc032)<br>Generation of packaging waste per capita (cei_pc040)<br>Generation of plastic packaging waste per capita (cei_pc050)<br>Recycling rate of all waste excluding major mineral waste (cei_wm010)<br>Recycling rate of packaging waste by type of packaging (cei_wm020)<br>Recycling rate of waste of electrical and electronic equipment (WEEE) separately collected (cei_wm060) |
| Connections conditions (TA1, TA2, TA4) | Reversible connections | [20, 76–78] | Resource productivity (cei_pc030) |
| | Standardised connections and fasteners | [79] | |
| | Modular construction | [8, 75, 80] | |
| | Standardised labelling | [81] | |
| | Minimise structural elements used | [82] | |

(continued)

**Table 13.10** (continued)

| Circularity criteria for BC&S | | | Related indicators from eurostat monitoring framework |
|---|---|---|---|
| Category | Criteria | Source | |
| Regulations and documentation (TA5) | Guides for the use of building materials efficiently<br>Protocols for incentivisation of CE practices use<br>Procurement that covers circular products<br>Voluntary agreements<br>Sequence of disassembly, recommended tools, and safety guides | [75, 83] | Private investment and gross added value related to circular economy sectors (cei_cie012)<br>Patents related to recycling and secondary raw materials (cei_cie020) |
| Stakeholder involvement | Initiatives on reuse<br>Construction companies that prioritise the use of circular methods and components<br>Stakeholders' engagement in the design process<br>Training | [75] | Persons employed in circular economy sectors (cei_cie011) |

- Material Import Dependency & EU Self-Sufficiency for Raw Materials (higher import dependency of BC&S from other countries rather than use of local resources, can lead to higher carbon footprint, this is why local materials should be preferred for circularity).

### *13.3.2 Construction and Demolition Waste (C&DW) Management*

Various indicators exist for evaluating the construction and demolition waste (C&DW) criterion, including reuse, recycling and recovery rates, the separate treatment of C&DW, and the extent and frequency of the reuse of BC&S. These indicators can be further detailed, as seen in Portugal's action plan for the CE, which measures the execution rate of the requirement to use a minimum of 5% recycled materials in construction [75].

Prioritising the use of recycled or reused materials over raw materials in construction and renovation processes is beneficial for resource conservation. However, the quality and condition of the recycled or materials to be reused materials are crucial in this case; therefore, it is essential to assess their quality and condition to ensure they meet the desired standards for structural integrity, appearance, and performance and health.

According to Eurostat's circularity criteria, such indicators can be related to BC&S for C&DW:

- Waste Generation per Capita: Lower waste generation per capita during the lifecycle of BC&S indicates improved circularity, as it implies less material being wasted.
- Generation of Waste Excluding Major Mineral Wastes per GDP Unit: This measures how efficiently components and systems are used to minimise waste.
- Generation of Packaging Waste per Capita and generation of Plastic Packaging Waste per Capita: These indicators relate to the packaging materials used for delivering BC&S, with environmentally sound packaging preferred for circularity.
- Recycling Rate of All Waste Excluding Major Mineral Waste: This measures how efficiently waste composed of components and systems is recycled for further applications.
- Recycling Rate of Packaging Waste by Type of Packaging: This indicator relates to the recycling of packaging materials used for delivering BC&S.
- Recycling Rate of Waste of Electrical and Electronic Equipment (WEEE) Separately Collected: This indicator relates to circularity practices in the electrical systems of buildings.

### *13.3.3 Connections Conditions*

In the implementation of a CE, the connections between the BC&S should be designed as demountable units that can be easily separated and removed without causing damage to attached elements and parts [78]. This involves using reversible connections, such as bolts or screws, click connections, velcro connections, and magnetic connections, instead of permanent adhesives, welds, or complex fixtures [76, 77]. These connections facilitate the reuse of recovered elements and components [84], and help achieve functional independence [20].

Standardisation of connections is also an important enabler for circularity, as standardised connections and fasteners enable quick and simple assembly and disassembly. Additionally, standardised connections compensate the need for standardised components and elements, simplifying the process and further supporting circularity [79].

The utilisation of modular construction techniques enhances circularity process by enabling easy assembly and disassembly of building components [75, 80]. Modularity is a significant enabler for adaptability, allowing for design simplicity and facilitating spatial system modification and transformability [8].

Implementing standardised labelling systems with clear identification tags or markings on BC&S can greatly aid in their identification, sorting, and tracking during disassembly [81]. This ensures that components are used to their fullest extent and in the best way, serving circularity.

Minimising the number and variation of structural elements used can reduce the number of connections required [82]. The Resource Productivity criterion from the Eurostat monitoring framework for CE relates to the efficient use of structural elements, minimising possible waste and allowing further disassembly through circular construction methods, such as dry connections and modular structures.

### *13.3.4 Regulation and Documentation*

The development of comprehensive regulations and documentation to guide CE implementation incentivises the stakeholders to use circular methods and engage in circular procurement. Circular procurement involves using products that comply with CE requirements, providing clear guidance to the whole construction value chain, from clients to maintenance staff and disassembly teams [75, 83].

Developing appropriate information on the disassembly sequence, recommended tools, and precautions is essential for safe and efficient disassembly. Eurostat provides relevant criteria such as Private Investment and Gross Added Value Related to Circular Economy Sectors. This indicator is connected to investments in circular construction practices, which can enhance circularity in BC&S. and Patents Related to Recycling and Secondary Raw Materials. Additionally, application of indicator Patents Related to Recycling and Secondary Raw Materials related to innovative BC&S construction methods can improve circularity in the construction industry.

### *13.3.5 Stakeholder Involvement*

Stakeholders play a vital role in developing circularity-related initiatives and prioritising the use of circular methods and components [75]. Engaging suppliers and manufacturers in the design process is crucial for exploring and appraising circularity solutions, particularly in system/component selection, component design, and disassembly strategies. Encouraging collaboration among value chain stakeholders can help identify opportunities to enhance the disassembly potential of products and systems.

The Eurostat criterion, Persons Employed in Circular Economy Sectors (cei_cie011), is relevant to this circularity criteria category. This indicator can relate to the workforce involved in sustainable and circular construction practices.

## 13.4 Case Studies on Best Practices for Circularity at Component and System Levels

### *13.4.1 Wire Arc Additive Manufacturing (WAAM) for Steel Production*

The focus on the CE in metal construction production has heightened industrial interest in novel steel production technologies, particularly Wire Arc Additive Manufacturing (WAAM). WAAM offers significant potential to reduce the environmental impact of manufactured products compared to traditional subtractive approaches [85]. The primary advantages of WAAM include reduced material waste, the flexibility in designing and fabricating complex geometries, and the ability to repair damaged components. However, relatively few studies have specifically examined the environmental impact of WAAM due to the novelty of this manufacturing process.

Shah et al. [86] conducted a comparative cradle-to-gate Life Cycle Assessment (LCA) to evaluate the environmental impact of a WAAM steel beam compared to a conventionally manufactured hot-rolled steel I-beam. The study considered carbon steel and stainless-steel materials, using a 2-m span steel I-beam as a benchmark. The WAAM steel beams, one carbon steel and one stainless steel, were designed using topology optimisation algorithms. The environmental impact was evaluated using the ReCiPe 2016 method, considering eighteen midpoint impact categories.

The results showed that WAAM beams resulted in a 7% and 24% reduction in climate impact compared to I-beams for carbon steel and stainless steel, respectively. The main benefit of the WAAM beams was the significant reduction in overall mass due to topology optimisation. For WAAM beams, the printing process was the primary contributor to their climate impact, accounting for up to 50% of the production impact when using carbon steel and 32% when using stainless steel. Factors such as deposition rate, shielding gas, and electricity usage significantly influenced the final environmental impact. The study also demonstrated that transitioning to a 100% renewable energy mix in WAAM production could result in a climate change impact reduction of over 30%.

### *13.4.2 Renovation of Old Existing Buildings Using Aerogel Insulation*

Adopting CE principles in existing buildings can reduce materials used in renovation projects, improve their energy performance and sustainability, and lower harmful emissions embodied in building materials [87].

Key indicators for evaluating building energy performance in line with CE principles include transmission losses, heating and electricity energy consumption, GHG emissions, thermal comfort, and maintenance costs [88, 89]. While new buildings can be designed for high efficiency and CE, many existing buildings fail to meet CE criteria. The challenge lies in applying CE strategies to these buildings to enhance sustainability, energy efficiency, and life cycle, thereby reducing $CO_2$ emissions, energy consumption and costs.

Older buildings, particularly those from the Modernist era, were often constructed with inadequate thermal insulation materials. Modernist architecture, built during the twentieth century with revolutionary new materials, abandoned traditional local materials that had proven sustainable in the past. This shift has led to significant problems in terms of energy efficiency, thermal comfort, and sustainability [90]. The 20th-century building stock, still in use today, continues to face issues related to high energy consumption, pollution, and poor thermal comfort. These buildings need to be renovated to meet the energy efficiency and CE criteria.

Proper renovation using sustainable materials with low embodied energy can achieve both energy efficiency and circularity. However, preserving the original architectural appearance of these buildings during renovation presents an additional challenge. Selecting the right materials and applying them correctly during the renovation process is crucial for improving energy efficiency and circularity while maintaining the buildings' authentic appearance.

Aerogel-based building products are currently considered to be promising insulation materials mostly due to their high thermal properties and limited thickness. They have quite low embodied energy, which is significantly lower than that of traditional insulation products [91]. Aerogel thermal plaster, with a thermal conductivity of 0.028 W/m·K, e provides excellent insulation even in small thicknesses due to its nano-porous structure [92]. Aerogel can be mixed to develop green building materials with unique characteristics, making it highly suitable for application in green and sustainable buildings [93].

For historical buildings, aerogel plaster has a mild impact on authenticity, provided it is compatible with the original materials' chemical composition and can be easily removed without damage, requiring no additional fastening that could harm the original material [94]. Additionally, aerogel insulation is known for its breathability, which is crucial for historic buildings as it helps to prevent interstitial condensation. This breathability ensures that moisture can escape from the walls, thereby maintaining the building's structural integrity and longevity [95]. It offers great flexibility for application on uneven surfaces and complex architectural details [96]. Applying this material not only improves energy efficiency and sustainability but also protects buildings from climate conditions and extends their lifespan. Due to its composition and method of application, aerogel plasters can perfectly mimic different textures, making it difficult to distinguish from the original while preserving the underlying material Silica aerogels have numerous applications and can be modified to meet various specific purposes required by the CE [97].

To evaluate the energy performance of buildings before and after applying aerogel thermal plaster on the façade, a software analysis was conducted on a selected case study building. This involved dynamic energy simulations of both the building's existing condition (actual scenario) and the renovated scenario using state-of-the-art energy analysis software. The key indicators assessed included energy consumption, emissions, transmission losses, costs, and thermal comfort.

The analysis showed significant improvements in the building's energy performance in the renovated scenario with aerogel thermal plaster. The results indicated a 65% reduction in heating energy consumption, which implies substantial financial savings for maintaining thermal comfort. This improvement in heating energy consumption, a key indicator of energy efficiency, led lower maintenance costs and enhanced thermal comfort.

Despite the high heating energy consumption, the building also consumed electricity for heating. In the coldest months, the heating system did not adequately maintain thermal comfort, necessitating additional electrical heating. In addition, the simulations revealed high energy consumption for cooling during the summer, underscoring the building's initial poor energy efficiency. However, in the renovated scenario, the average monthly total electricity consumption was reduced by 40%.

Electricity consumption is a critical indicator for evaluating improvements in energy efficiency, thermal comfort, and financial costs. The reduction in electricity usage in the renovated scenario further supports the effectiveness of aerogel thermal plaster. Comparisons of the building's monthly $CO_2$ emissions between the actual and renovated scenario were conducted. The results showed a 50% reduction in monthly $CO_2$ emissions in the renovated scenario. Reducing emissions is a key indicator not only for evaluating energy improvements but also for CE implementation through proper building renovation.

A financial analysis of the building's maintenance costs revealed that annual costs for heating and cooling were reduced by 49% in the renovated scenario. The highest costs were observed during the winter months, while the lowest were during periods when the outside temperature was closest to the indoor temperature. This highlights the significant role of thermal insulation in reducing maintenance costs.

The implementation of CE in culturally valuable old buildings, particularly Modernist buildings, remains a global challenge. The analyses carried out for the renovation of these buildings using aerogel plaster, which aligns with CE measures, energy efficiency, sustainability, and, above all, with the conservation of their authentic appearance, have become state-of-the-art methods for evaluating the key indicators affecting CE practices.

### *13.4.3 Green Roofs Using Recycled Substrates: A Pilot Experience at the University of Córdoba, Spain*

Green roofs offer a passive thermal regulation technique by acting as natural insulators that prevent solar radiation from directly affecting the underlying roof. Additional benefits and ecosystem services delivered by green roofs include thermal and acoustic isolations, rainwater collection and retention (which moderates flooding events and improves runoff water quality), reduction of air pollution, aesthetic enhancement, protection of the roof's waterproofing layer, increased biodiversity, and $CO_2$ capture [98]. Quantifying the energy-saving potential of green roofs is essential for their effective incorporation into building construction protocols as nature-based solutions in urban environments.

The University of Córdoba (UCO) in Spain implemented a green roof case study to evaluate its energy performance. This involved characterising external meteorological variables, monitoring the humidity evolution of substrates based on meteorological conditions and the irrigation strategies, assessing thermal damping, and measuring heat flows and energy savings in various recycled substrates. The substrates included mixed recycled sand from a C&DW treatment plant containing ceramic particles, concrete, plaster, more; and two typical green roof substrates comprising organic materials (mulch, coconut, and black peat) and volcanic gravel. Humidity and temperature sensors were installed at different depths on the green roof.

During a summer season, Hayas et al. [99] found several key results: (i) there was a significant difference in water retention behaviour among the substrates, with recycled aggregates enhancing water retention capacity; (ii) green roofs reduced maximum temperature peaks during summer, delaying the peak temperatures inside the building; (iii) the reduction in maximum temperatures was clearly linked to the moisture content of the substrates, as higher humidity decreased insulating effect; and (iv) green roofs positively impacted the energy balance, offering savings between 62 and 93% compared to non-green roof.

The green roof pilot at UCO was also tested for other objectives, including evaluating the risk of contamination via leaching from the vegetation substrates. The results indicated: (i) all analysed materials were classified as non-hazardous; (ii) sulphate content in all materials exceeded the limit for inert classification; (iii) some materials had chloride content above the inert limit; and (iv) zinc concentration in one material exceeded the inert material limit. However, leachate from a green roof would be diluted when mixed with rainwater and wastewater, considerably reducing the concentration of both chloride and sulphate anions [99].

## 13.5 Conclusions and Remarks

This chapter has emphasised the importance of considering circularity criteria and indicators at both the component and system levels of building assembly, aiming to reduce environmental impact and resource consumption through reuse, recovery, and recycling, as assessed via Life Cycle Assessment (LCA). CE principles in construction promote the selection of renewable, recyclable materials with low embodied energy. Transitioning from high-carbon-emission materials to low-carbon-emission alternatives is crucial for fostering CE in the construction industry. However, this requires a shift in the mindset of stakeholders, including architects, engineers, and builders, who must move beyond the traditional assumption of an unlimited supply of disposable materials.

The CE model represents a regenerative system aimed at achieving economic growth while minimising energy consumption and resource depletion. It is founded on three fundamental principles: eliminating waste through design, restoring and rejuvenating natural systems, and promoting continuous material utilisation. Assessing a building's energy consumption during its production, operation, and EoL phases can be achieved by collecting data on BC&S. This data helps determine the building's energy consumption and ensures compliance with international environmental standards and certifications. By quantifying this data using numerical scales or qualitative approaches, BC&S can be ranked according to their circularity levels. Unsatisfactory rankings can prompt feedback to manufacturers, designers, and other relevant stakeholders, encouraging improvements in design, materials, or manufacturing processes to enhance circularity. Assessment findings can be digitally logged and shared with stakeholders to promote transparency and informed decision-making. Regular monitoring of the building's serviceability and health status ensures adherence to evolving CE practices and industry standards.

Given the significant potential for implementing CE principles in the building industry, future research should focus on developing and refining circularity criteria and indicators tailored for BC&S to better understand their impact on overall building circularity. It is essential to ensure that systems have functional independence, which can be achieved through reversible connections, and to explore how incorporating circularity principles can create new business opportunities and reduce waste disposal costs.

Embracing circularity in building design is essential for achieving a more sustainable future. This involves designing for disassembly and adaptability to facilitate the reuse and recycling of building components, using recycled materials to reduce the embodied energy of materials, and minimising waste throughout the building's lifecycle. While much remains to be explored, the case studies presented demonstrate the potential for circularity in the building industry. More research and case studies on best practices are needed to provide evidence of the benefits of circular BC&S and their impact on overall circularity and sustainability levels in buildings. Continued research and implementation of circular practices will be crucial to ensuring safe, reliable, and sustainable buildings for all.

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